Geodynamics workshop in the Czech Republic

Organized by O. Cadek[1] and D. A. Yuen[2]

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INTRODUCTION

The first geodynamics workshop in the Czech Republic, following the Velvet Revolution in 1989, was held this summer (28 July to 31 July 1993) in the village of Pistina, in southern Bohemia, close to the Austrian border.

The 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 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 if 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 Department 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 programme also included a tour of a 14th century brewery and the historical town of Trebon. This tour was enjoyed by all who participated.

The 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.

WORKSHOP SUMMARY

First day

Adam Dziewonski (1) led off with a discussion of the upper-mantle tomography, where he compared his results with those of Zhang and Tanimoto. 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 (3)on the changes in the power-spectrum of 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 (7,9) 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 (4) 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 5000x5000 were solved by the direct method.

Toshiro Tanimoto (6) discussed the inversion of the global-scale crustal structure. He employed fundamental modes out to periods of 40 s 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 (5)** 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 (11)** then discussed about 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 (17) presented a novel technique based on a genetic algorithm for nonlinearly inverting the 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 (15)** found to be very interesting , as it might indicate the presence of some amounts of garnet in the transition zone.

Reini Boehler (7) presented his results on the melting of perovskite up to 650 kbar. High melting temperatures, in excess of 7000–8000 K, could be extrapolated to the core–mantle boundary. 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 (22)** discussed the differences in the topography between the 400 km 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 (10)** presented results of calculations of the thermal-kinetic equations associated with non-equilibrium phase-changes in sub-ducting slabs. **Karato (14)** discussed the inner-core anisotropy due to magnetic field-induced preferred orientation of iron. **Franck (12)** presented results on the preferential wave-lengths arising out of chemical reactions at the core-mantle boundary. **Peltier (19)** discussed the possibilities of an extremely low viscosity zone lying above the 670 km discontinuity, which can satisfy the geoid data. **Dziewonski**'s colourful 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.

Second day

On Thursday **Shun Karato (15)** 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 (16)** 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.

Dick Peltier (32) discussed the pulse of the earth from the periodic oscillations found from the numerical simulations of flush events in a 2Daxisymmetic model. The hypothesis that the Nusselt number would decrease with increasing Ra , due to increased layering, was introduced. **Ctirad Matyska (30)** 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 as being capable of producing the megaplumes observed in seismic tomography of the lower mantle.

In the afternoon the focus of many of the 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 (35)** 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 (44)** who focused on 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 moments 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 (27)** presented 3D 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 a surface Rayleigh number going to $4x10^8$. In this afternoon session videos were shown for all of the talks on convection with phase-transitions. The effects of the compositional boundary on mantle convection were discussed by **Ulli Hansen (26)**. He pointed out the novel effects of depth-dependent properties on producing focused 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 (36)** presented results on 3D large-aspect-ratio convection with temperature-dependent Newtonian and non-Newtonian rheolgoies, where large aspect-ratio cells were found for effective Rayleigh numbers of around $5x10^5$. **Lada Hanyk (13)** 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 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 and Yuri Podlachikov (23)** 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 Cloetingh (33)** presented results on sea-level variations from compressional stresses and the influences of small-scale faulting on producing intermediate timescales , less than 10^6 years, fluctuations in the sea-level. **Fritz Busse (24)** presented results on the thermal-blanketing effect for aspherical-shell model. **Hana Kyvalova and O. Cadek (28)** displayed their results of correlation between former subducting sites against five different tomographic models. The results below 1500 km depth appear to be important in connection with the potential flush events in the mantle. **J. Nedoma (41)** gave a lengthy presentation of equations to be used in geodynamical modelling.

Third day

On early Friday morning at 2 o'clock Slava Solomatov at long last arrived at the workshop after being detained at the Czech border . Later that morning **Fritz Busse (37,38)** led off with a general discussion of mean-flow mechanisms in various geophysical fluid dynamic 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 (43)** 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 why the degree two harmonic is considered so dominant. Its relationship to the flush events was also emphasized. **Jerry Moser (40)** 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's evolution in high Rayleigh number convection. **Slava Solomatov (34)** gave a talk on the three different regimes in strongly temperature-dependent convection. As the rheological strength increases, plate-like behaviour was predicted by this model based on asymptotic analysis of the mean-field solution. Later, in the bar, he and Dave Stevenson presented 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 to this theoretical model.

B. Steinberger and R. O'Connell (42) 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^{-1} on absolute plate velocities. **Shigeo Yoshida (46)** 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 Vermeersen (45)** discussed the role played by recent tectonic uplifts on observed vertical motions and its impact on postglacial rebound. His use of linear viscoelastic theory for treating this problem with intermediate timescales was questioned by Peltier.

Panel discussion: last day

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 measurement of phase changes and rheological changes during phase transitions. Another heated discussion centred 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 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.

SEISMOLOGY

1 Negative velocity anomalies in the mantle: from mid-ocean ridges to the core–mantle boundary

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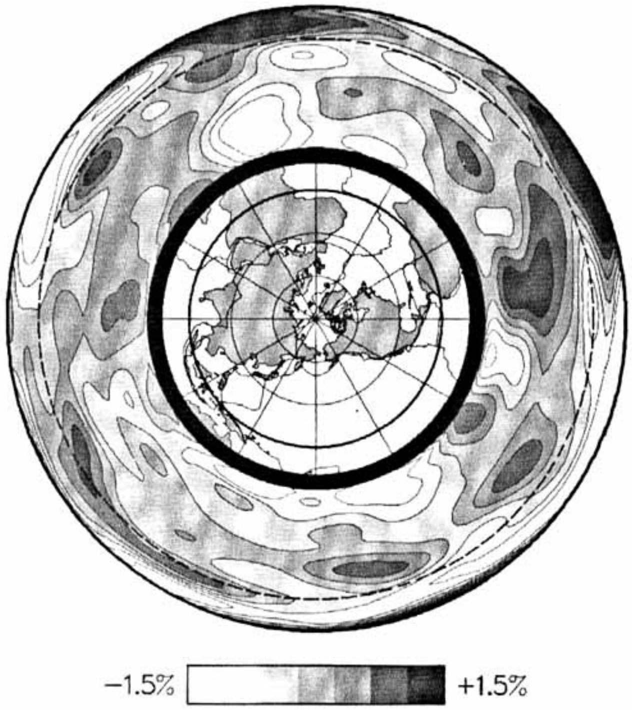
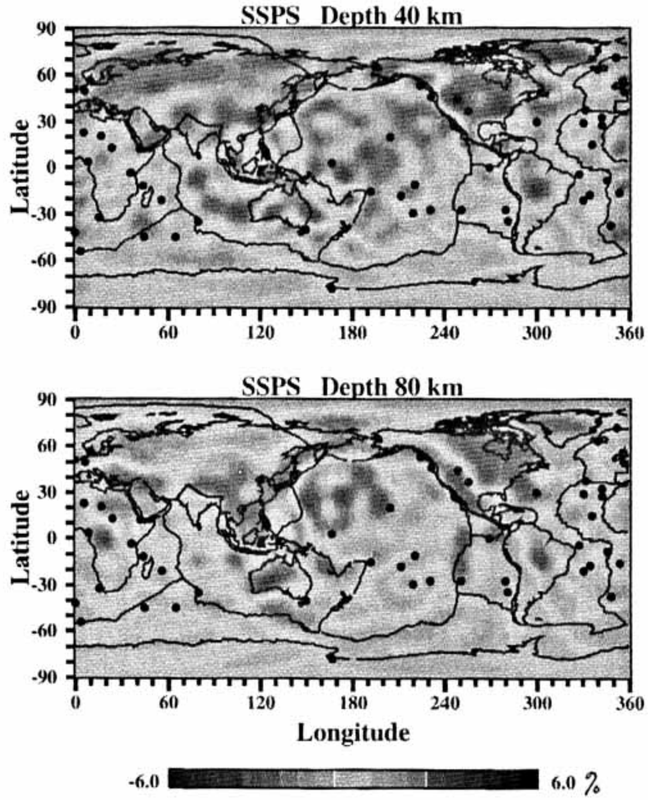
The relatively deep origin (300–500 km) of the East Pacific Ridge anomaly has been proposed by Wielandt and Knopoff (1982) and is predicted by model M84C of Woodhouse and Dziewonski (1984). It is also consistent with the differential travel time data of Woodward and Masters (1991), as shown by more recent modelling efforts involving different types of data (Dziewonski and Woodward, 1992; Woodward *et al.*, 1993). This is in 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 from 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 3D geometry, the image of velocity anomalies in the lower mantle in adepth 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 relationship between the circum-Pacific subduction zones and the location of the high velocity anomalies in





Left: *this figure is a cross-section through the equatorial plane of model SH/!2/WM13 (Su, Dziewonski and Woodward). The thick circle inside the inset map indicates the great circle defining the cross-section. The outermost ring is the Moho surface, the innermost corresponds to the core–mantle boundary. The 670 km discontinuity is indicated by the dashed line. The range of the relative velocity perturbation is ±1.5%.*
Right: *Tanimoto's detailed crustal inversion showing the transition of the continental and oceanic crust between 40 km and 80 km depth. Anomalies are given 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

2 Large 3D structure of shear velocity in the mantle

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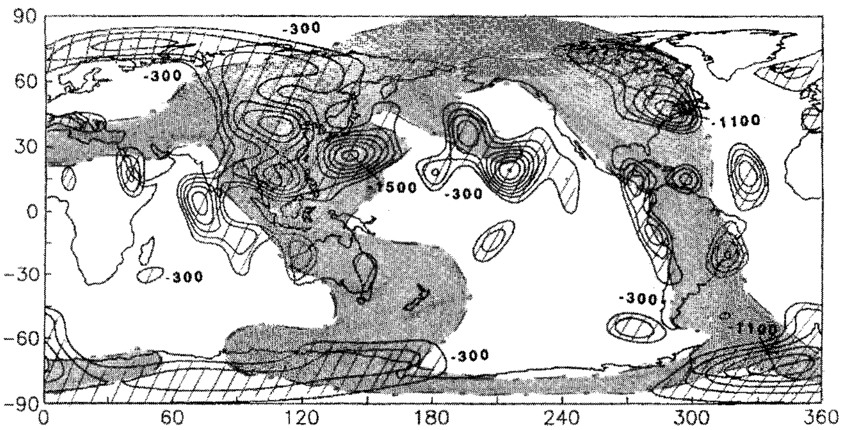
A data set consisting of 27,000 long-period seismic waveforms and 14,000 seismic travel-time residuals has been assembled. The waveform data include body-wave and mantle-wave seismograms. Roughly one half of the data has been collected by Woodhouse and Dziewonski (1986), but the other half contains data from new seismic networks: GEOSCOPE and CDSN, which significantly improve the global coverage. The travel-time residuals consists of absolute travel-times (S and SS; Su and Dziewonski, 1991; Su, 1993) and differential travel-times (SS-S and ScS-S; Woodward and Masters, 1991a and b) measured from digital seismograms using a cross-correlation technique. These data are simultaneously inverted for a 3D 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 basic functions using spherical harmonics up to 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 1700 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.



Correlation of past subduction sites with cold anomalies deduced by seismic tomographical models. Work has been carried out by H. B. Kyalova, O. P. Cadek, D. A. Yuen and L. M. Weyer. The shaded section represents the site of past subduction since the Cretaceous. Data have been taken from Richards and Engebretson (1992). Contours with slanted line background represent the cold anomalies (in degrees colder than the surrounding mantle) which have been obtained by converting the seismic tomographic data of Y. Fukao and by using mineral physics involving relating thermal to seismic anomalies. The depth is at the core–mantle boundary (CMB).

3 Mapping the core–mantle transition

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The core–mantle boundary (CMB) is one of the most important internal boundaries of the Earth. Its properties are determined by the evolution of the Earth as well as by recent processes in the Earth's interior. The CMB itself determines also dynamics of the Earth, especially by core–mantle coupling. Up to very recent time there were only theoretical speculations and considerations concerning apossible topography of the CMB and lateral heterogeneity of the D''-layer. Seismological investigations have shown the possibility of the existence of both features (Dziewonski, 1984; Morelli and 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 and Jurdy, 1984) show a certain correlation with the seismologically determined features of the core–mantle transition zone. These facts indicate that there should be some common deep situated sources correlation, possibly in the structure and/or in the processes of that region of the Earth's interior. Diffracted seismic waves bear information about the base of the mantle and the core–mantle boundary. Digitally recorded P_{diff} 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 P_{diff} 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)

4 Confidence regions for mantle heterogeneity

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

Results are not optimistic for travel time tomography using agenerous set of rays, a10° by 10° model parameterization, and an idealized error model. On a global scale, the mantle's velocity structure is nearly consistent with a radially symmetrical 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

5 Tomographic model of upper mantle shear attenuation

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A new tomographic model of upper mantle shear attenuation derived from mantle Rayleigh wave data was presented. 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 focusing 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 recording 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* parameterization, and the scale of lateral heterogeneity resolved corresponds to that achieved in aspherical 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.

6 Short-period upper mantle tomography

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In the global-scale seismic velocity studies, shallow structures were determined by relatively long period surface waves, usually for periods longer than about 80–100 s. Because such surface waves are affected by crustal thickness and velocity, crustal models were assumed and their effects were subtracted from measured phase velocities. In short-period surface waves, this causes a major change in pattern. Consequently, assumed crustal structure has a dominant effect on the solution. This procedure is not a problem if we know crustal structure accurately all over the Earth; unfortunately this is simply not the case. One possible solution to this is to analyse short-period surface waves and constrain crustal effects by these measurements, rather than using assumed crustal structure. The surface wave analysis was extended to about 40 s. The procedure in phase measurement is similar to Zhang and Tanimoto (1992, 1993), but all measurements, including path selections and expansion of the data sets, were done from scratch. The number of data examined was expanded to 30,000, but strict selection of data limited the data to 6000 for Rayleigh waves and 4000 for Love waves, smaller than the number used by Zhang and Tanimoto but is nonetheless sufficient to determine the spherical harmonic coefficients up to degree and order 20 (total number of parameter is 441). A ray tracing procedure was included in the analysis, since short period data may require consideration of deviation from great circle paths. However, since I use only minor-arc waves, such effects turned out to be small overall. There are of course some cases for which path deviates substantially, but those are small in number. Short period toroidal mode (Love wave) data for angular degree l>150 and short-period spheroidal mode (Rayleigh wave) data (l>about 200) demonstrate that phase velocity is low in continental regions and fast in oceanic regions. This is a completely predictable result from the variations of crustal thickness, but it makes quite a contrast with fast velocity in old continents and slow velocity in tectonically active regions that we have become accustomed to in the last 10 years. Inversion for S-wave velocity variations with depth shows that familiar patterns (fast velocity in shields, etc.) emerges at about 80 km in depth, thus shallower velocity patterns in previous global earth models are not valid any more. Below 80 km, previous models appear quite accurate. The main contribution of this study is then for structure in the upper 100 km. In the map for S-wave velocity for depth 50–70 km, one of the slowest areas is Himalaya, well known for its thick crust by regional seismic studies. It also demonstrates thick crust under Andes, eastern to middle parts of USA as well as the Baltic shield and Siberia. Of course, what we observe is slow velocity anomaly and is thus not necessarily a thick crust. Slow anomaly in western US is in the area of Basin and Range and is thus more likely to be shallow, high temperature anomaly there. Similar arguments can be made for anomaly in the northern part of the Mediterranean Sea. Signatures for hot-spots as well as ridges are confirmed and similar features to Zhang and Tanimoto (1992, 1993) are found. It does seem clear, however, that the results in Zhang and Tanimoto represents a rather highly damped solution and a less damped solution provide better depth resolution.

MATERIALS AND VISCOSITY

7 Temperature regimes at the base of the lower mantle

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Seismic anomaly structures at the bottom of the lower mantle may be interpreted in terms of large temperature variations based on new laboratory data at very high pressure:
(i) Sound velocity measurements at mantle pressures show an increase in $d \ln \rho / d \ln \upsilon$ with depth. This and the strong decrease in the thermal expansion coefficient, yield 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/T_m-values between 0.3 and 0.4. This strongly decreases the temperature dependence of viscosity if the viscosity-systematics found at low pressure are applicable at lower mantle conditions;
(iv) 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.

8 The rheology of $Mg_{1.83}Fe_{0.17}SiO_4$ olivine and modified spinel at high pressures and temperatures

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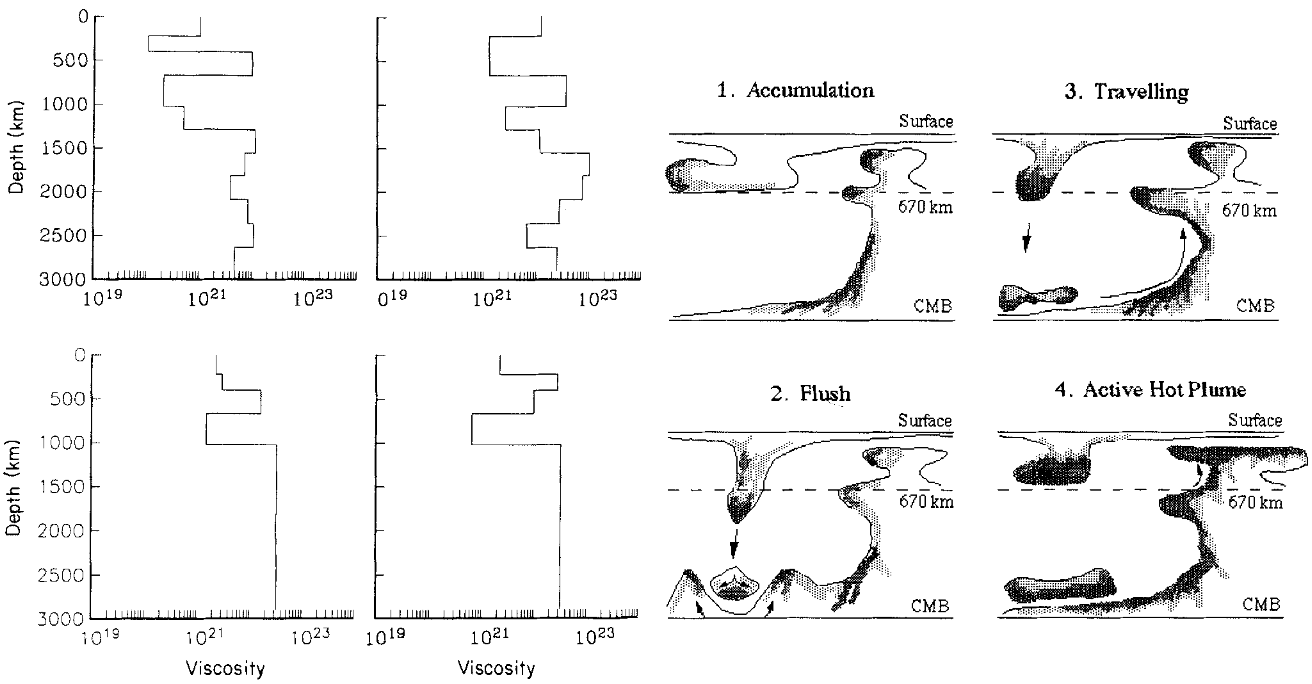
Knowledge of the rheological properties of deep mantle mineral assemblages is a prerequisite for construction of reliable models of mantle convection and deep focus earthquakes. Although we now have reasonable low pressure data for the rheology of olivine $(Mg,Fe)_2SiO_4$, the dominant upper mantle mineral phase, there is a paucity of experimental constraints on the pressure dependence of the constitutive equations describing its flow behaviour at depth. This is due principally to the restrictive low-pressure range available to classical experimental deformation apparatus (< 3 GPa). Furthermore, even assuming the simplest case of achemically homogeneous mantle, $(Mg,Fe)_2SiO_4$ olivine undergos several phase transitions between 400 km and 700 km depth (13–24 GPa). As a consequence, the rheological behaviour 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 behaviour are being investigated experimentally. In order to address this problem, olivine and its high-pressure polymorph β-phase have been experimentally deformed at high confining pressures and high temperatures using a 6–8 large volume multi-anvil apparatus. Amodified assembly design permits the semi-quantitative uniaxial compressive deformation of specimens at



Left: *radial models of mantle viscosity by Scott D. King. These results have been obtained by using a genetic algorithm. This figure illustrates clearly another class of models that have not appeared in the more traditional studies. These models are characterized in general by high-viscosity transition zones and a pronounced low-viscosity zone generally deeper down, but sometimes shallower than the transition zone. King emphasized that these models can produce equally good fits to the observed geoid, based on the χ^2 variance reduction.* Right: *schematic diagram showing the sequence of events related to the flushing event associated with the cold material collected at the transition zone. This was presented by Satoru Honda.*

high confining pressures (16 GPa) and high temperatures (1600°C). Sample strain rates can be determined from the displacement rate of the loading ram and yield stresses are estimated using available piezometers. Preliminary results on $Mg_{1.83}Fe_{0.17}SiO_4$ polycrystalline olivine aggregates at6 and 14 GPa are consistent with single crystal dislocation creep laws (stress exponent n = 3.5) assuming apressure dependence (activation volume V*) of the order of 5 cm^3mol^{-1}. The experiments also suggest that the deformed high pressure olivine poly-morph mboxbeta-phase has a viscosity greater than that of olivine by a factor of 5, for experimental strain rates of 10^{-6} s^{-1} at 15 GPa and 1450°C.

9 Sound velocities of four minerals to very high compression: constraints on d ln ρ/ d ln velocity

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The transverse and longitudinal acoustic modes in MgO to 400 kbar, yttrium aluminum garnet to 600 kbar, aluminum oxide to 630 kbar, and $MgAl_2O_4$ to 120 kbar measured in the sideband fluorescence of chromium 3+ in the crystal lattices directly yielded the shear and compressional sound velocities with aprecision 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 acompression 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: d ln ρ/ d ln υ at constant temperature. We find this parameter and their pressure derivatives to be nearly the same for all four minerals: about 0.7 for V_p and 0.95 for V_s at 1 atm which increases substantially with pressure along trends very nearly equal to the seismically derived global average. At high pressures, it is expected that d ln ρ/ d ln υ at constant pressure approaches the constant temperature derivative because of decreasing anharmonicity. This is corroborated by recent ISS measurements by Chai *et al.* (*EOS, Trans Am. geophys. Un.*, **73**, 523, 1992) and Zaug *et al.* (*Science*, **260**, 1487–1489, 1993). The effects of anelasticity on the value of d ln ρ/ d ln υ in the lower mantle are small and decreasing with depth since lower mantle temperatures are at less than half of the homologous temperatures T/T_m of the candidate minerals (see Boehler *et al.* abstract number **7**). Thus, an increasing value of d ln ρ/ d ln υ and decreasing thermal expansion with depth allows calculation of lateral temperature variations from seismic anomalies using:

$$\delta T=(1/\alpha)(d\ \ln \rho/d\ \ln \upsilon)\ (d\upsilon/\ \upsilon)$$

(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.

10 The effects of phase transition kinetics on subducting slabs

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We have investigated the effects of kinetics on non-equilibrium aspects of the olivine to spinel transition in a descending slab. Our 1D 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-dependencies of the kinetics, is included in the energy equation. Mathematically this problem is governed by a system of coupled differential equations consisting of (i) 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 inhomogeneous driving term due to the nucleation rate, (ii) the temporal variation of the pressure which includes the pressure from the descending slab and the pressure changes due to phase kinetics, and (iii) a 1D nonlinear parabolic equation for the temperature taking into account diffusion, latent heat release and adiabatic heating. 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 $cmyr^{-1}$ 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^{-1} the metastable olivine region may be pushed down to adepth of around 600 km, where the phase boundary is very sharp due to latent-heat effects.

11 The effect of 3D viscosity variations on mantle flow and convection-related surface observables

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

12 Chemical differentiation at phase transitions in downgoing slabs

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In the present investigation we study a physical mechanism that may cause a chemical differentiation at a polymorphic phase transition. The idea is based on the simple view that during the density increase at the transition there is the appearance of strong stress-fields that act on the constituents of a solid material. In particular so-called incompatible ions with ionic radii not appropriate for the high-pressure phase may drift to the grain boundary and reach high-diffusivity paths so that in this way they may be enriched in the low-pressure phase. It is important that our proposed mechanism of differentiation is not related to partial melting as in the usual models in geochemistry but acts in a solid. Therefore, this mechanism may be favoured at depths greater than 200 km where partial melting does not seem easily possible, as follows from investigations on the temperature distribution and the melting curve in the Earth's mantle. Numerical estimations confirm 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.

13 The impulse response of a visco-elastic earth with a spherical viscosity

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Although the problem of viscoelastic gravitational relaxation of a spherically symmetric earth has been studied for a number of years, attempts to fit all the observables to the model have not been fully successful. Differences between the predicted and the observed 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 emphasized that the coupling due to the lateral variations of viscosity only affects the r.h.s. terms and the spectral o.d.e.'s remain separated according to order and degree. The method was tested for spherically symmetric case by comparing its results with results obtained by standard methods based on the Laplace transformation. The first computations indicate that the accuracy of the method is satisfactory. An application of the method to complex viscosity structure will require further numerical tests.

14 Importance of anelasticity in the interpretation of seismic tomography

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Temperature derivatives of seismic wave velocities are the key parameters in the interpretation of seismic tomography. In most of the previous studies, the temperature derivatives determined at high frequencies are used, which involve only the effects of anharmonicity. It is shown, however, that temperature derivatives due to anelasticity (including visco-elasticity) 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.

15 High creep strength of garnets and its bearing on the dynamics and chemical evolution of the mantle transition zone
Shun-ichiro Karato, Zichao Wang and Kiyoshi Fujino, *Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55415, USA*
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 min-eralogically-induced rheological stratification (heterogeneity) have important effects on the dynamical behaviour 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 enhancing layered convection and explaining the fixity of hot-spots and deep earthquake activities.

16 Dynamic topography compared with residual depth anomalies in oceans and its effect on the age–depth curve
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Dynamic topography induced by mantle flow would affect the large-scale variation of ocean depth. Ocean depth is generally expressed as a function of crustal age; that is age–depth curve. Regional bathymetric deviation from the age–depth curve, the 'residual depth anomaly', would indicate the dynamic topography if local isostatic anomalies are avoided. In this study, we first made a global residual depth anomaly map. Secondly we predicted geoid and dynamic topography by using density perturbations converted from seismic tomography models and additional slabs. We found that both the predicted geoid and dynamic topography have good amplitudes and correlations with the observations when density perturbations in shallow part of the upper mantle were imposed by slabs, not by tomography model. This means that velocity anomalies detected by seismic tomography in this depth range do not represent well the density perturbations. Finally, an effect of dynamic topography upon the age–depth curve was examined. We found corrected age–depth curve, determined by depth data after removal of the predicted dynamic topography, continued to increase its depth until 110 Ma while the uncorrected curve flattened at older than 70 Ma. This corrected age–depth curve suggests that the 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.

17 The genetics of mantle viscosity
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Several recent inversions for radial mantle viscosity structure, constrained to fit the geoid or plate velocities, find models with alow 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, acriterion 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.

18 Modelling post-glacial rebound effect on VLBI baseline vector evolution
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The final late Pleistocene deglaciation event of the current ice age was sufficiently massive (inducing in excess of 120 m of eustatic sea-level rise) and recent (ending just 4000 yr 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 3D 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 aspherically 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 arealistic model for the space-time history of the global ice sheets, as well as agravitationally 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.

19 The radial profile of mantle viscosity: constraints from postglacial rebound- and tomography-based convection models

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Past and continuing analysis of the data of postglacial rebound, including relative sea level data, earth rotation observations, and to some (!) degree free air gravity anomalies, suggest that the contrast in viscosity between the upper and lower mantle may be modest. Best fitting two layer parameterizations, for example, require lower mantle viscosity near 2 × 1021 Pa s if the upper mantle value is fixed to the now classical value of 1021 Pa s first inferred by Haskell on the basis of his analysis of postglacial rebound data from Fennoscandia. In contrast, many recent inferences of the depth dependence of mantle viscosity based upon seismic tomography constrained models of mantle convection have led their authors to conclude that the upper mantle–lower mantle viscosity contrast must be extreme, with ratios of 100 or higher being preferred. The non-hydrostatic geoid observations on the basis of which the latter inference has been made are inherently non-unique, however, and there does exist at least one class of models (first analysed by Alessandro Forte) that allows simultaneous reconciliation of both postglacial rebound and convection related constraints. This class of models is characterized by the existence of athin layer (say 70 km thick) lying immediately above the endothermic phase transition at 660 km depth and in which the viscosity is quite low, say about 1019 Pa s if the viscosity of the overlying material is 1021 Pa s. Such models have geoid kernels that are essentially identical to the kernels for models that have upper mantle and transition zone viscosity that is everywhere two orders of magnitude lower than in the lower mantle. Since the thin layer is not 'visible' to postglacial rebound data, this class of models simultaneously satisfies the rebound constraints. This clearly has important implications insofar as the issue of transient rheology is concerned and therefore to the understanding of the physics of mantle creep. Both postglacial rebound and convection related inversions will be discussed in this paper from the perspective of expectations based upon *a-priori* models of mantle convection that include phase transition effects.

20 The sharpness of upper mantle discontinuities: constraints from non-equilibrium phase transformations in convective systems

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Seismic data indicate that the upper mantle discontinuities at 410 and 660 km are sharper than could be expected for equilibrium phase boundaries. We suggest that sharp discontinuities can be formed in achemically homogeneous mantle as acombined effect of the kinetics of phase transformations and convection. Despite high temperatures of the 'normal' mantle and fast crystal growth, kinetics are important within afew 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 behaviour 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.

21 Geoid anomalies from Cenozoic subduction in semi-dynamical flow models including a phase boundary

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In order to investigate the relationship between the geoid and plate subduction, we develop a 3D 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 Myr. 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 amoderate 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.

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22 Transition zone Clapeyron slopes, seismic topography, and chemical contrasts

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The depths, widths, and magnitudes of the 410 km and 660 km seismic dis-continuities are largely consistent with an isochemical phase change origin, as is the observation that the topography on these discontinuities is negative correlated and significantly smaller than predicted for chemical changes. While most thermodynamic studies of the relevant phase changes predict greater topography on the 410 than the 660, recent seismic studies suggest the opposite effect. This might be consistent with a few recent thermochemical studies which suggest that the Clapeyron slopes of the perovskite-forming reactions may exceed in magnitude those of the spinel-forming reactions. However, we have re-examined 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 α–β transition in slab interiors. Additional constraints upon possible upper-lower mantle compositional contrasts will also be reviewed.

23 Faulting of a brittle lithosphere during extension/ compression on a ductile substratum

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Extension/compression of a brittle layer on a ductile layer is a basic model for a number of tectonic processes ranging from salt tectonic scale up to lithosphere/ asthenosphere 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 afault population from an initial continuum, we used a numerical grid from 10,000 up to 60,000 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 ranges 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 centimetres. Second negative conclusion is about using of visco-plastic approach for modelling 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.

24 Time periodic convection in a spherical shell of a high Prandtl number fluid with a thermal blanket

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Convection in a spherical system of two superimposed fluids is analysed 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. (1978) A model of time-periodic mantle flow, *Geophys. J. R. astr. Soc.*, **52**, 1–12, 1978.)

25 On the chemical reaction zone at the core–mantle boundary (CMB)

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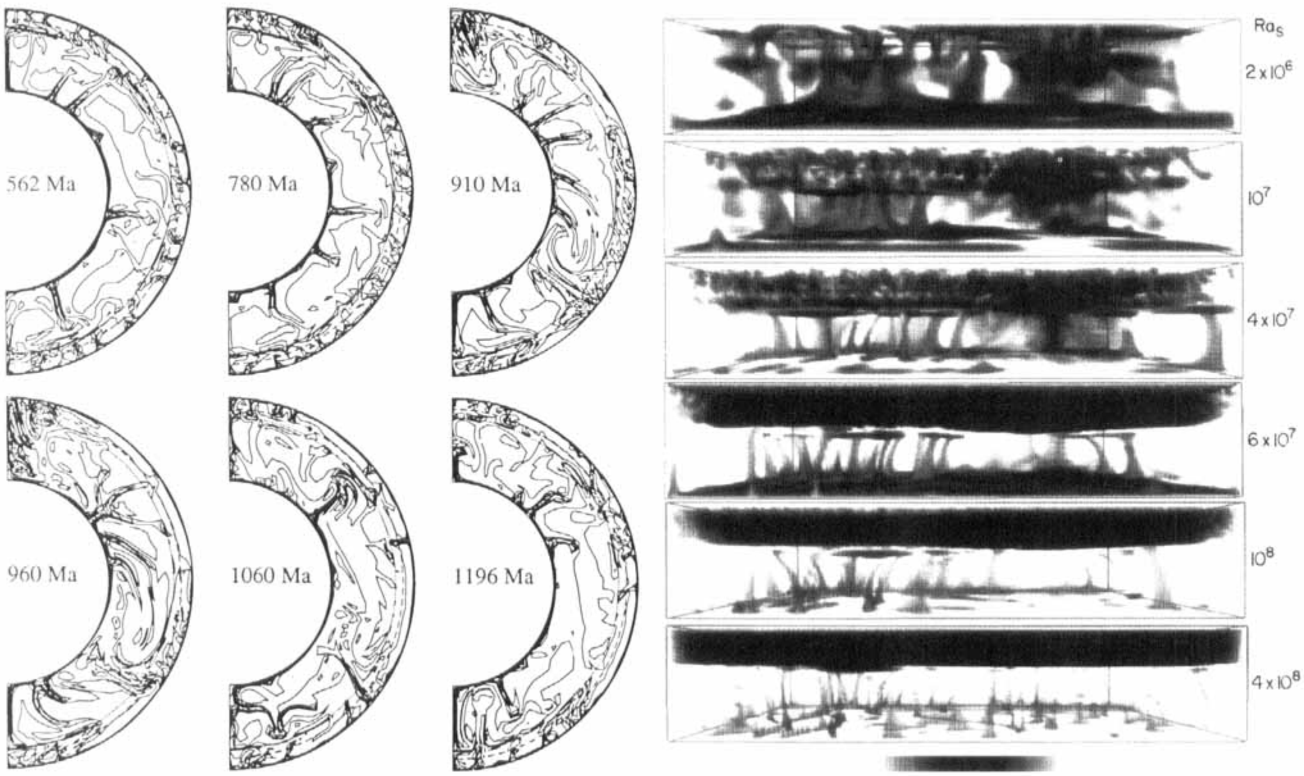
The core–mantle reaction in the Earth's interior proceeds in two scales: a short-scale chemical reaction leading to local equilibrium and a large-scale dispersal of reaction products. Both processes are described with the help of the diffusion equation in spherical symmetry. It results, that the infiltration and reaction of fluid iron into the mantle can be as far as 103 m over a time scale of about 1017 s. The large-scale dispersal of reaction products is connected with a growth of the CMB-radius up to an order of about kilometres 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 $2 < l < 6$. In this way our mechanism may explain the generation of large undulations of CMB with small amplitudes.



Left: *the evolution of the temperature field within the mantle from a 2D axisymmetric spherical convection model operating in the regime of statistical equilibrium. Work has been carried out by W. R. Peltier and L. A. Solheim. The Rayleigh number is 10^7. The model contains both the olivine–spinel and the spinel–perovskite transitions. At 562 Ma and 780 Ma the flow is strongly layered. Intense flush events, characterized by high mass flux across the 660 km horizon, are clearly evident at 910 Ma and 960 Ma.*
Right: *The effects of Rayleigh number on the style of layering for a cartesian model with major phase transitions. Work has been carried out by D. A. Yuen, D. M. Reuteler, S. Balachandar and J. L. Smedso. Rayleigh number is based on surface valuees. The volumetrically averaged Ra is given by 0.2 times the surface Rayleigh number.*

26 The dynamics at an interior boundary in the earth's mantle with depth-dependent material properties

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The style of convection in the Earth's mantle is likely to change with depth, either in a gradual fashion, due to the gradual change of material properties and/or in a more discontinous manner, due to discontinuities in the mantle's transition zone. The decrease of the coefficient of thermal expansion alpha and the increase of the viscosity υ with pressure have been demonstrated to influence the style of convection in a gradual way. Small -scale heterogeneities are present in the upper mantle while in the lower mantle large-scale heterogeneities do prevail. Phase boundaries and/or compositional boundaries within the transition zone are potential candidates which can act to separate convection into separate circulation systems, thus giving rise to an abrupt change in the convective velocities and in the thermal field. By numerical experiments, carried out in two-dimensional domains with finite elements, we have investigated the role of a compositional boundary within amantle where the viscosity increases and the thermal expansivity decreases with depth. Although the depth-depenence of α and υ 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 focusing 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'.

27 Role of phase transitions on the mantle dynamics

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Mantle phase transitions play an important role in the mantle dynamics. Numerical simulations of 3D 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 ashort 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 3D up to asurface Rayleigh number of 10^8. For this large Ra, the 3D 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 included an animation of 3D convection.)

28 A detailed correlation analysis between subduction in the last 180 Myr and the seismic structure of the lower mantle

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We have used the latest tomographic models based on both P and S waves together with the reconstruction of subduction in the last 180 Myr (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 acontinuous 3D distribution of seismic anomalies we have applied both the standard technique of correlation analysis, based on L_2-norm scalar product of two fields given in terms of spherical harmonics, and non-standard methods based on evaluation of line integrals. The results of our analysis confirm arather 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.

29 Plates and plumes

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It is proposed that tectonic plates can affect mantle plume morphology by determining the temperature drop across aplume source layer. Numerical convection models demonstrate how the introduction of plate-like behaviour in aconvecting 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.

30 Are the superplumes caused by radiative heat transfer?

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The seismic tomography revealed broad blob-like low velocity anomalies in the lower mantle beneath Africa and the Pacific (e.g. Su and Dziewonski, 1991; Woodward *et al.*, 1993). Corresponding thermal anomalies obtained by means of recent mineral physics data exceed several hundreds of degrees (Yuen *et al.*, 1993). Numerical models of mantle convection with constant physical parameters show, on the other hand, narrow plumes with very small life-time. Depth-dependent viscosity and thermal expansivity lead to stable larger plumes as shown by Moser *et al.* (abstract **40**.

In this contribution, we consider radiative heat transfer which can be described by a strongly temperature dependent (T3) 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 astrong stabilizing effect on mantle upwellings and the creation of large hot temperature anomalies (superplumes) with high temperatures in the centres. This suggests the importance of radiative heat transfer for the lower mantle dynamics.

Su W. and Dziewonski A.M.(1991) Predominance of long-wavelength heterogeneity in the mantle, *Nature*, **352**, 121–126.

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

31 The origin of the hot thermal boundary layer at the core–mantle boundary in the cooling earth

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We have examined thermal evolution of the convecting mantle thermally interacting with the core using two-dimensional dynamical convection models with constant or temperature- and pressure-dependent viscosity in arectangular 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. Acontact of a cold plume with the CMB takes the heat away from the core and the temperature in the core is homogenized by the efficient heat transfer. That is, the horizontal temperature heterogeneity of the mantle above the CMB and its thermal interaction with the core are two major phenomena controlling the heat release through the CMB. Therefore, the temperature difference between the mantle and the core is fairly reduced, if both the phenomena are taken into account. The hot plume originated at the CMB suggests the existence of the internal heat source in the core. The present amount of the internal heating of the core is estimated to be in the range from 2.0×10^{12} W to 6.0×10^{12} W.

32 Phase transition mediated mantle mixing: implications for the Wilson Cycle

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At sufficiently high Rayleigh number near 107, at which *a-priori* models of convective mixing adequately reconcile the observed mean heat flow through the Earth's surface, the dynamic impact of the Olivine-Spinel and Spinel-post Spinel transitions at the respective depths of 400 and 660 km is extreme. Axisymmetric anelastic calculations demonstrate that the flows in this regime are dominated by an intense time dependence that is controlled by abi-modality of behaviour in which the circulation executes spontaneous 'flips' from astate of layered convection into astate of predominantly whole-stability of the thermal boundary layer that develop across the endothermic transition at 660 km depth when the Clapeyron slope for this transition is set to a negative value equal to that required by high pressure experimental data. The hallmark of transitions from the layered state to the whole-mantle state is the development of intense 'avalanches' of cold material from the upper mantle and transition zone into the lower mantle. These events are qualitatively similar to those imagined to occur in the so-called 'regolith' model of Ringwood which was not based upon a dynamically consistent analysis of mixing in the presence of phase boundaries. In our model of mantle convection these events impose aprofound degree of long range order on the large-scale circulation such that surface material that is as distant as 10,000 km from the point immediately overlying the downwelling is drawn towards it. The downwellings themselves, with lifetimes of order 100–200 Myr, therefore develop basins of attraction within which all continental fragments would be brought together. One is thereby led to a view of the so-called supercontinent cycle (sometimes referred to as the Wilson Cycle) in which the aggregation phase is controlled by a major avalanche event. Once an avalanche occurs our model demonstrates that the thermal boundary layer at 660 km depth reforms and the flow returns to the layered state. In this layered state the underside of the supercontinent becomes subject to attack by the small-scale convection cells that control the radial heat transport through the upper mantle in this regime. Rifting occurs and the cycle eventually repeats. Our models do provide an explanation for the timescale of 600 Myr that appears to characterize this quasi-periodic phenomenon.

33 Quasi-cyclic reorganization of fault systems in deforming brittle lithosphere: mechanism for third-order relative sea-level changes?

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Faulting of brittle lithosphere causes changes in topography and, therefore, contributes to the relative sea-level variations. Alicyclic long-term changes of state of stress and rheological properties (due to strain softening) of the lithosphere during faulting contributes to the second order variations in tectonic subsidence rate. Quasi-cyclic reorganization of fault systems may be related to third-order variations and may happen even under conditions 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 the level required to initiate slip in a new fault. The typical subsidence/uplift rate of a few millimetres per year yields times of a few million years to initiate a new fault, which is consistent with the periodicity of third-order relative sea-level changes. The tectonic subsidence/uplift produces alicyclic sedimentary records in the neighbourhood 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 stress variation of 2 kbar is essential to cause the typically observed magnitudes of third-order relative sea-level changes.

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

The results show that Forsyth's model is appropriate only for thicknesses of the brittle layer of the order of 100 km (cold continental lithosphere) and only for particular sets of strain-softening parameters. For other parameters (i.e. 20 km thickness of brittle layer or ideal plastic rheology), lateral spacing (distance between simultaneously acting faults) became too narrow to cause deviation from the 1D model, and, in particular, there was no significant shortening of the time required to reactivate a new fault system and to decrease 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, possible because of the differences in time scales, may yield important information about the regional structure of the lithosphere.

34 Regimes of variable viscosity convection: from constant viscosity to plate tectonics

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

35 Layered and non-layered structures in convection with phase-transitions

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We used a finite element method to model mantle convection with temperature-dependent viscosity and phase-transitions. The effects of the deflection of the phase boundaries and latent heat release were incorporated into the model by formulation of an effective thermal expansivity. Both the olivine-spinel and spinel-perovskite transitions at 400 and 670 km depth, respectively, were considered. In this framework, the effects of temperature-dependent viscosity, secular cooling of core and mantle, and of the existence of a triple-point in the β-γ-spinel-perovskite system on the flow structure were investigated. Compared to models with constant viscosity, temperature-dependence has two major effects on the flow structure. The mean temperature of the lower mantle is approximately 350 K higher than in the constant viscosity case. This high temperature and the additional release of latent heat at the spinel-perovskite-boundary diminish the viscosity near 670 km depth and lead to an effective mechanical decoupling of upper and lower mantle flows. Due to this decoupling little mass exchange between upper and lower mantle is observed and the temperature drop in the transition zone is increased by approximately 100 K. The recently measured very high melting temperatures of the lower mantle imply that in this case the transition from β-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 2D and 3D calculations show similar behaviour 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.

36 Time-dependent 3D convection with strongly temperature-dependent, non-Newtonian rheology

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The major features of mantle convection (e.g. plates, plumes) are greatly affected by or even caused by the strong temperature-dependence of mantle viscosity. Non-Newtonian creep may also have important effects. However, previous 3D 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, 3D 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 (n points) operations is obtained, but the robustness of the procedure to large viscosity contrasts is reduced. Even so, variations of 3 orders of magnitude are readily modeled, and 4 or 5 orders are possible with care. The scheme is easily parallelizable, and has been implemented on the Intel Delta and iPSC/860 parallel supercomputers.

Preliminary time-dependent solutions in a wide aspect ratio (8×8×1) 3D box are presented, for cases with constant, temperature-dependent and temperature- and stress-dependent viscosities, with order 10^3 viscosity variation.

ROTATION

37 Generation of mean flows in planetary systems

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

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

38 Core–mantle coupling and the geodynamo

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

39 Mantle rheology, convection and rotational dynamics

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

40 The dynamical influences of depth-dependent properties on inducing large-scale upwelling structures in planetary mantles

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The appearance of large-scale upwellings in the lower mantle in seismic tomographical models runs counter to the intuition and past experiences derived from modelling using constant physical properties. Recent work by Hansen *et al.* (1993) in acartesian 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 2D results have already been observed in 3D cartesian models with similar depth-dependent properties (Balachandar *et al.*, 1992). We have constructed afinite-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 robous tplumes in the lower-mantle. These giant plumes are nurtured even more for planets with smaller cores. There giant plumes with plume-heads, spanning twenty to thirty degrees, can exist at polar regions for effective Rayleigh numbers in excess of 10^6. The influences of these giant plumes or 'yeldas' on rotational dynamics also show up in phase-space portraits of the evolution of the moment of inertia and Nusselt numbers. The timescales associated with temporal changes of moments of inertia are longer than those associated with global heat-transfer,as shown by the phase-space analyses.

41 Numerical simulation of geodynamic processes in the 2D and 3D Earth. A new approach to mantle–core coupling studies. Theory

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The mechanism of geodynamic processes which take place in the Earth's interior is simulated here by the thermo-visco-plastic Bingham rheology. The influence of magnetic, diffusion and gravity effects will be taken in account. The phase change boundaries, like a melting, recrystallization and solidification of the Earth's rocks in the lithosphere, the mantle and the core, as well as metallized/nonmetallized and ionized/nonionized rocks under high pressure and high temperature, will be investigated theoretically. Convection in the Earth's mantle and thermomagnetodynamic turbulence in the Earth's core are much studied but little understood. Numerical calculations and investigations of 2D and 3D geodynamic processes, suggest that the magneto-thermo-hydrodynamic turbulence in the core and the thermal convection in the mantle in time and pressure dependent viscosity, created by compressible or incompressible Earth's materials, respectively, are possible only by using numerical methods, namely by using the finite element or the finite difference methods. In the real Earth all geodynamic and geomagnetic processes are coupled. Seismic and geomagnetic investigations show onto the layered thermo-visco-plastic upto thermo-visco-strongly plastic (liquid) structure with melted or recrystallized zones, respectively, in a relatively weak magnetic field. Recent investigations of high pressure show on metallized behaviour of Earth's rocks under high pressures. Therefore, the thermo-visco-plastic Bingham rheology is acceptable for the whole Earth interior. The system of equations follow from the principal laws of physics. The velocity field is related to the density field in amoving fluid by the conservation law of mass. The fundamental equations for the moving thermo-viscoplastic media of the Earth follow from the law of momentum conservation. The equation for the geothermal field in the Earth interior follows from the general conservation law of energy. Due to melted and recrystallized zones in the mantle as well as in the lithosphere and due to melted core–mantle boundary the formulation in enthalpy is suitable to use and therefore will be used in the contribution. The stress-strain rate relation is defined by

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

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

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

Solving this problem we obtain a realistic 2D or 3D velocity, magnetic, geothermal and gravity fields existing in the electrically conducting Earth's body, namely in the electrically conducting core and mantle and therefore we can study their coupling. Since such problem is analytically unsolved, only numerical approximations come into consideration. In the contribution it will be shown that the problem leads to solve the system of variational inequalities and variational equalities. Since analytical methods and the method of spherical harmonic analysis are not known for such types of problem, only the numerical methods can be used. For the numerical solution the semi-implicit scheme in time and the finite element approximations in spatial variables will be used. The scheme obtained is a stable one. The algorithm solving such a problem will be given. Since we obtain the discrete values of velocity, magnetic, geothermal and gravity fields, the presented method permits thermoelectric and thermo-galvanomagnetic effects in the Earth interior to be studied, i.e. the effects at interface boundaries of two different conductors originating from flowing currents with simultaneous electric and magnetic fields and gradient of temperature, as well as those originating from current penetrating through the interface boundary between two different conductors. It is possible due to the numerical solution of the problem which was found at discrete points of the Earth body.

42 Coherent motion of Pacific hot-spots due to flow in the lower mantle

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Although the motion of Pacific hot-spots relative to each other is much slower than their motion relative to the Pacific plate, they may exhibit a coherent motion due to large-scale flow in the lower mantle. This may bias our estimate of the 'absolute' plate velocity. We investigate how fast Pacific hot-spots may move coherently. We make the following assumptions: (i) Hot-spot plumes originate at the core–mantle-boundary at aposition which is advected with the large-scale mantle flow. (ii) Plumes rise vertically relative to the ambient flow and the rising velocity is inversely proportional to the viscosity of the penetrated mantle material. (iii) Plumes do not change the mantle flow. The mantle flow field is calculated from plate velocities and lateral density hetero-geneities. For the present time, the latter are inferred from seismic tomography. For past times, density heterogeneities are advected back in time using the same flow field. For the computation we use the method of Hager and O'Connell. We perform calculations for different viscosity structures and different conversion factors from seismic velocity anomaly to density anomaly. Preliminary calculations, which were done for stationary mantle flow, give the following results, which are in accordance with observational data on Pacific hot-spot chains. Slow relative motion of hot-spots implies high viscosity of the lower mantle (~ 1023 Pa s). Due to flow in the lower mantle in a direction opposite to the plate motion, there may be a coherent motion of several Pacific hot-spots. This may bias estimates of 'absolute' plate velocity by about 2 cm yr^{-1}, since the hot-spot reference frame is to alarge deal defined by Pacific hot-spots. Our results may help to explain the observed correlation between motion of the Pacific plate and the net rotation of the lithosphere in the Cenozoic.

43 Does mantle convection know about Earth rotation?

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It is widely appreciated that by the traditional criterion (smallness of the Coriolis force) mantle convection does not 'feel' the effect of Earth rotation. It is less well appreciated that this is not the only issue. There are at least four other issues that must be considered: (i)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. (ii)The non-central gravity vector of the rotating Earth causes a drift and change of the convection pattern and favours 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. (iii)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 away 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° cm[1]) changes in HORIZONTAL temperature gradients. (iv)Tidal heating has a latitudinal variation that will affect large-scale flows through the temperature dependence of the viscosity.

44 The effects of phase transitions in 3D spherical models of mantle convection

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Numerical modelling 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 km 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 3D spherical geometry many flushing events are in progress at agiven time, so individual events do not have the large effect on globally-averaged quantities predicted by 2D or 3D 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 (in all, 40% of total). Examination of the radial flow field at different wavelengths indicates that long wavelengths 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); nevertheless, comparison of radial correlation functions for tomographic and numerical models favours 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.

45 Changes in the Earth's rotation by tectonics

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Whereas the present-day true polar wander and the secular non-tidal acceleration of the Earth have usually been attributed to post-glacial rebound, it has been suggested recently 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, *Geophys. Res. Lett.*, **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 assess these tectonic contributions further, 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 modelled 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 modelling 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.

46 Effects of the core–mantle interactions on the geomagnetic field

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The core–mantle coupling is essentially important to the understanding of the dynamics of the Earth's core. Thus I have investigated theoretically two kinds of core–mantle couplings, topographic and thermal. Comparison between my theory and observations of the geomagnetic field reveals new evidence 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 adecadal 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 alonger time scale also appears to be strongly affected by the topographic coupling. Thermal coupling is important for the geomagnetic field on along time scale. I have investigated thermal response of the outer core fluid to the sectorial temperature heterogeneity of the CMB under the assumption of quasi-geostrophy. The locations of upwellings and downwellings are found to be controlled by the strength of the toroidal field. I have inferred the strength of the toroidal field of the outer core by comparing the observed field with the theory.