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Theoretical and Observational Studies of the Earth's Mantle

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Abstract

This project concerns the dynamical transport of heat and matter in Earth's mantle and core. Mantle convection shapes the surface by building mountains, dispersing and aggregating continents, and guiding the structure and evolution of the environment at Earth's surface; on short time scales, it causes earthquakes and volcanic eruptions. Through thermal transport it also affects patterns of heat flux out of the core, which in turn influences convection in Earth's fluid outer core. Convection of core fluid maintains the geomagnetic field, which, at the surface, affects navigation and communication and helps to shield Earth from cosmic radiation. We undertake computer-intensive studies of the 3-dimensional dynamics of the mantle and core through both simulations and analyses of observational data. Fluid dynamic model predictions are compared to field and seismic observations. The research exercises LANL hydrodynamic codes and brings their operators into contact with a broader world of computational research. It supports related missions in treaty verification and hazard reduction.

Background and Research Objectives

The governing intent of this research is understanding geodynamics, the internal and surface motions that govern Earth's evolution. Regions of interest extend from the surface to the inner core. Thus, at the surface there have been claims in the past two decades that supercontinents insulate the mantle so that heat builds up beneath them. Although such claims have found wide support, they remain to be tested. The continental insulation hypothesis is largely based on recognition that the seismically slow mantle below the Atlantic-African geoid high coincides with the former location of Pangea. However, similarly hot regions exist below large oceanic plates like the Pacific, which has neither been covered nor traversed by a continent in 500 Myr. Our approach is to use a modified 3-dimensional numerical mantle convection model to test the viability of continental insulation by varying both plate and mantle properties. The efficiency of continental insulation is quantified by calculating the rate of change of the average temperature in the subcontinental mantle.

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Global plate tectonic motions and related geological processes, such as earthquakes and mountain building, are driven by the internal heat engine of Earth's rocky mantle, which extends from the base of the crust to the molten iron outer core. Heat transfer in the mantle is dominated by convection, which causes warm upwelling flow and cold downwelling flow on length scales ranging from tens to thousands of kilometers, and on timescales of millions of years. The solid mantle flows via ductile creep of its constituent minerals (mostly olivine and pyroxene in the upper mantle), so that mantle convection occurs in a rather exotic "fluid" whose creep strength, or viscosity, may vary by orders of magnitude with changes in temperature and pressure from the surface plates to the core-mantle boundary (CMB). Modeling this process of convection, along with brittle failure near the surface that causes plates to form, is a major challenge in Earth sciences. One approach is to use the massively parallel three-dimensional spherical mantle convection code TERRA. This permits very large viscosity variations (many orders of magnitude), and such viscosity variations can be handled flexibly for both temperature- and stress-dependent rheologies. We have used such methods to synthetically image convection models, performing perhaps the most realistic tests of resolution of global seismic imaging to date.

The principal goal of dynamo calculations is to gain a better understanding of the origin, structure, and evolution of the Earth's magnetic field by comparing 3-dimensional numerical simulations of convection and magnetic field generation in the Earth's outer fluid core, i.e., the "geodynamo," to geomagnetic and paleomagnetic observations. We are using the Glatzmaier-Roberts model, the first dynamically consistent 3D-computer model of geodynamo (Glatzmaier and Roberts, 1995a,b, 1997a,b,c). In geodynamo simulations, a non-uniform pattern of heat flux imposed over the core-mantle boundary can significantly affect properties of Earth's magnetic field.

Importance to LANL's Science and Technology Base and National R&D Needs

The strength of this collaboration is the combination of computer modeling expertise of Los Alamos scientists and the theoretical and observational expertise of university scientists. This research is multi-disciplinary, i.e., fluid dynamic (computer) model predictions are compared to field and seismic observations. Of course, it is also multi-institutional, i.e.; it involves collaboration among Los Alamos scientists, university professors, postdoctoral scientists, and graduate students from several universities. Core competencies in hydrodynamic computation are particularly involved.

Scientific Approach and Accomplishments

Geodynamo

Having simulated a magnetic field that is qualitatively similar to the Earth's (at least outside the core) in terms of its intensity, dipole-dominated structure, and westward drift of its non-dipolar structure, we now are trying to understand why there are different frequencies of dipole reversals at different times in the paleomagnetic reversal record. To accomplish this we have conducted a series of geodynamo simulations that test the influence the mantle has on convection and magnetic field generation in the core. Core convection is vigorously driven below cold mantle, where the fluid is strongly superadiabatic, and is inhibited below hot mantle, where the fluid is locally subadiabatic. The radial heat flux pattern at the core-mantle boundary (CMB) during a particular period of Earth's history has been controlled by mantle convection. However, the time scale for mantle convection is a million times longer than it is for core convection. Therefore, to simulate different geologic times, we conduct geodynamo simulations with different (static) patterns of heat flux imposed over our CMB, while keeping the total heat flow out of the core at 7.2 TW (2.2 TW of which is due to the mean superadiabatic temperature gradient). Except for a uniform heat flux case, we set the peak variation of heat flux to be three times greater than the mean superadiabatic heat flux at the CMB.

A 200,000-year simulation with uniform heat flux at the CMB has not reversed, shows no tendency to reverse, and has a smaller secular variation than does the present day geomagnetic field. Two other 200,000-year simulations were also run, but with heat flux at the CMB patterned after the wave number two-dominated seismic tomography of the Earth's present lower mantle (Figure 1a); one reversed once, the other reversed twice, and they both display somewhat larger secular variation than does the present day geomagnetic field. This example illustrates how local thermal winds, driven by the heterogeneous heat flux boundary condition at the CMB, can destabilize the fluid flow in the outer part of the fluid core enough to trigger a magnetic dipole reversal.

To investigate the dependence on the particular pattern of heat flux at the CMB, we conducted five other simulations with simple heat flux patterns at the CMB. One that is antisymmetric with respect to the equator with no longitudinal variation (Figure 1c) has resulted in the greatest secular variation and several reversals. This demonstrates how this imposed heat flux pattern is incompatible with the style of convection that is preferred in a rapidly rotating low-viscosity fluid shell, like the Earth's outer core. Another pattern (Figure 1b) tests the sensitivity to a heat flux that varies in longitude. Although this pattern is not as disruptive as that of Figure 1c, it also resulted in several reversals within a hundred thousand years. Two axisymmetric patterns have been tested (Figures 1d and 1f), one forcing more heat out of the equatorial region and the other out of the polar regions.

Both show less secular variation than the others do, but both have reversed once in a hundred thousand years. Finally, a pattern that has the heat flux peaking in both the polar regions and the equatorial region (Figure 1e) shows the least amount of secular variation and no tendency to reverse. These results suggest that the Earth may have had a temperature structure in its lower mantle similar to the reverse of Figure 1e (because high temperature mantle results in low heat flow from the core) during superchrons (long times of no reversals).

Another topic is the magnetism of the ancient Earth. Rock paleomagnetism indicates that the geomagnetic field has existed for much or all of Earth's history. It is widely believed that, at the present time, the field is created by a convective dynamo that is powered by the cooling of the Earth, which releases latent heat and light constituents of core alloy as the heavy constituents (predominantly iron) freeze on the inner core boundary. These thermal and compositional buoyancy sources drive core convection. Earlier in Earth's history, the inner core was much smaller, or absent. The convectional driving from the inner core is then less important and buoyancy arising from bulk cooling of the fluid core becomes more significant. Somewhat to our surprise, it was found that 7.2 TW, the assumed that the heat flux out of the core, is insufficient to maintain a dynamo when the inner core was substantially smaller than at present. This may be attributed to the fact that bulk buoyancy is inefficient in driving convection in contrast with buoyancy created by bottom sources. Nevertheless, by increasing the heat flux out of the core to 12.7 TW, dynamo action could be maintained apparently indefinitely.

The ancient dynamo has a different character from the ones that we have simulated for present day Earth. Figure 2 shows contours of equal total current strength J (as a snapshot and for just one meridional slice through the core) for both the present Earth and for an Earth in which the inner core has one quarter of its present radius. The former indicates that today's field is generated almost entirely by currents flowing within the tangent cylinder, that is a cylinder parallel to the rotation axis and touching the inner core at its equator. In contrast, the current system supporting the ancient field is spread out throughout the core.

Although the magnetic field leaving the core in our present day dynamo models tends to be concentrated near the poles, much more so than for the ancient core models, it spreads out with height, so that differences between the models at Earth's surface are less marked. It will therefore be difficult to determine paleomagnetically when in the geological past the inner core was born and how it grew. Three recent independent estimates have been made of the age of the inner core, with results ranging from 1.2 to 1.4 billion years. These all assumed, implicitly or explicitly, that the heat flux from the core is much smaller than the 12.7 TW indicated by our work. The implication is that the inner core is even younger than so far estimated.

Mantle Convection

Until recently, most computer models of mantle convection have been artificially restricted to two-dimensional geometry or to unrealistically coarse spatial resolution. Only recently have three-dimensional models in spherical geometry with appropriate resolution (<100 kilometers) been feasible within the limits of modern parallel supercomputers. These models have been developed mainly by Los Alamos scientists Gary Glatzmaier and John Baumgardner, in collaboration with faculty and graduate students at UCLA, Caltech, and UC Berkeley. Glatzmaier's approach uses spherical harmonic analysis of temperature, pressure, and velocity fields, and this approach was employed in achieving the first high resolution three-dimensional results (Tackley et al., 1993). Baumgardner's approach uses a multigrid finite element technique that is particularly adaptable to parallel processing. We have now developed Baumgardner's finite element code TERRA to include surface plates and strongly variable viscosity with sufficient global spatial resolution (50 km) to explore the extremely vigorous regime of convection in Earth's mantle (characterized by a dimensionless Rayleigh number exceeding 10^8). In addition, the code has been parallelized so that it can be run on most modern supercomputer platforms with excellent efficiency (using >90% of available cycles).

Our numerical modeling experiments have shown rather conclusively that viscosity stratification in the mantle has a first-order effect on the nature of convective flow, and we consider this to be a significant discovery (Bunge et al., 1996; Bunge and Richards, 1996). That other effects such as heating mode and mineralogical phase changes are relatively minor is also somewhat surprising. Because there is considerable independent evidence for an increase in viscosity by about a factor of 10-100 from the upper to lower mantle (Hager and Richards, 1989; Mitrovica, 1996), it appears that viscosity stratification must play a major role in determining the nature of mantle convection and plate tectonics. Indeed, global plate motions exhibit a spatial scale of upwellings (mid-ocean ridges) and downwellings (subduction zones) comparable to that seen in our stratified-viscosity models.

Using 128 processors of the NASA/Goddard Cray T3E, we obtain a global nodal spacing of 50 km, which should improve to 25 km within the next two years as larger machines come on line. TERRA now treats very large viscosity variations (about a factor of 10 node-to-node, or many orders of magnitude globally), and such viscosity variations can be handled flexibly for both temperature- and stress-dependent rheologies.

We have also explored the effects of surface plate motions in further organizing mantle convection and have performed the most realistic tests of resolution of global seismic imaging to date (Bunge et al., 1998). The plate-constrained mantle convection models reproduce quite well many of the features found by seismic tomography, including pronounced high-velocity structures beneath old subduction zones and the large-scale structure of slow and fast anomalies near the core-mantle boundary.

In a first effort at modeling mantle convection using the known global plate motions over the past 200 million years of Earth history, the combined effect of plate motions and viscosity stratification result in a pattern of convection dominated completely by cold downwellings at subduction zones (Figure 3). In the top panel, a depth shell of temperature variations is shown for a convection model whose surface plate motions have been constrained to be those observed. Cold downwelling structures are present beneath North and South America, reflecting subduction of the ancient Farallon plate as well as the modern Nazca and Cocos plates. Rough agreement between our model and the seismic velocity structure of Grand (1997) (lower panel) is noted, both in the long-wavelength (hemispheric) structure and in some details of the short-wavelength structure.

Another effort has two concerns: development of dynamically consistent tomographic models of the three-dimensional structure of the Earth's mantle that reconcile several seismic data sets and, in addition, a variety of geodynamic data sets; and development of an internal loading theory, based on the TERRA code, that will address the question of lateral viscosity variations and thus lead to more realistic geodynamic modeling of Earth's mantle.

Initial geodynamic investigations have focused on describing Earth's long-wavelength dynamic surface topography within the context of tomography-based viscous flow theories (with radially varying viscosity). We have carried out a detailed study of a new geodynamic data set, namely, the inference from Crust 5.1 [Mooney et al., 1998] for Earth's solid outer surface dynamic topography. Earth's dynamic surface topography corresponds to the component of the topography that is maintained by vertical stresses associated with the underlying mantle convective circulation. Dynamic surface topography highs/lows are maintained over upwellings/downwellings. In Figure 5, we show the very long-wavelength inference for this datum obtained by using the Crust 5.1 global crustal model to carry out an isostatic reduction of the observed topography. Systematic dynamic topography depressions of the order of 1-2 km over all continents represent a striking feature of this global map. Our modeling of this geodynamic field within the context of radially varying internal loading theories has led to two important observations. First, optimal descriptions of the inferred dynamic surface topography require that lower mantle (below 660 km) heterogeneity be precluded from contributing significantly to vertical stresses at the surface. This can be achieved by either imposing a large increase in viscosity across the depth of the 660-km seismic discontinuity within the context of whole-mantle circulation models or by explicitly layering the circulation at 660-km depth using a flow-blocking boundary condition. Second, dynamic surface topographic lows over continents require the existence of deep (approximately 400-km) and dense (approximately 1% above average) structure beneath continental plates. Then, as shown in Figure 5, an excellent global description of the Crust 5.1-based inference is obtained.

We anticipate that this research will allow us to gauge the importance of new tomographically imaged structures with respect to the general mantle convective circulation (e.g., the radial style of the convective circulation) and the prediction of geophysical fields (e.g., the nonhydrostatic geoid, the surface pattern of heat flux anomalies, dynamic surface topography, etc.).

In addition, we have recently focused on another development of TERRA [Bunge et al., 1996], a self-gravitating version with which we intend to treat lateral viscosity variations. This basically requires that we take into account contributions to the gravitational potential associated with deflected boundaries (dynamic deflections of the solid outer surface and the core-mantle boundary due to convection-maintained vertical stresses), in addition to the contributions due to internal loads. We have encoded the necessary expressions to carry out calculations of the gravity field and are currently investigating the accuracy of the solution for pressure, which is required for the computation of the boundary deflections. We are also in the process of crosschecking results that we obtained for the gravitational potential for a variety of problems that admit simple solutions.

To model near-surface dynamics we use the three-dimensional convection code MC3D developed cooperatively by researchers at Harvard University and Los Alamos National Laboratory. The 3D Cartesian geometry code has been benchmarked against several 3D mantle convection codes and has been used for a variety of studies. The version of MC3D used for this study has a modified plate formulation that allows us to prescribe stiff finite thickness plates.

To evaluate the efficacy of continental insulation we calculate the rate of change of the average temperature in the subcontinental mantle. Our results indicate that continental thermal insulation is reduced when the mantle is largely internally heated and when continental area is limited in both x and y horizontal directions (in contrast to the implicitly infinite extent of the plates included in 2D models).

Thus, MC3D has yielded the unanticipated, exciting result that a supercontinent (such as the one that from which our present continents are derived) need not be inherently unstable because it insulates the mantle that it overlies. By incorporating both oceanic and continental plates we find that oceanic plates impose a long wavelength flow on the regions they overlie, which raises the temperature in the mantle beneath to magnitudes comparable to and even in excess of those observed below a model supercontinent. We conclude that because the mantle is largely internally heated, subcontinental heating results from an absence of subduction rather than insulation of active upwellings. Accordingly, hotter-than-average regions may evolve below both large oceanic plates and supercontinents. These findings are supported by the vast hot region in the upper mantle observed by seismic tomography below the Pacific plate.

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Figure Captions

- Figure 1. Patterns of the radial heat flux imposed at the core-mantle boundary for six dynamo simulations. Solid (broken) contours represent greater (less) heat flux relative to the mean.
- Figure 2. Contours of electric current strength, J , shown (as a snapshot and for just one meridional slice through the core) for both the a model of the present Earth and for an Earth in which the inner core has one quarter of its present radius.
- Figure 3. Top panel is a thermal planform of the stratified viscosity convection model constrained by the past 200 million years of global plate motions. Middle and lower panels show fast and slow shear wave velocity variations mapped by seismic tomography. The model of Grand (1997) is developed from body shear waves.
- Figure 4. Cross-section through the equatorial plane of TERRA mantle convection calculation showing viscosity in color and transverse velocity with arrows. The viscosity varies by a factor of 200,000. The surface velocity has platelike coherence over notable angular distances.
- Figure 5. Crust 5.1-based inference of Earth's relative, long-wavelength (spherical harmonic degree range $L = 1 - 8$) dynamic surface topography and the theoretical prediction of this field based on viscous flow modeling. The preferred model assumes a high-viscosity lower mantle 200 times more viscous than the upper mantle and transition zone. Tomographic model SF1K/WM13 is employed in the calculations and the corresponding shear wave velocity anomalies are converted into density according to Karato's seismic conversion factor.
- Figure 6. Isosurfaces indicating nondimensional temperatures (T) in the mantle following a continental collision. $T=0.7$ (light shaded) and $T=1.09$ (dark). The elapsed nondimensional time (t) is indicated for each frame. At $t=0.0$ a continental collision is simulated at a convergent plate boundary [delineated by the light shaded downwelling in frame (a)] by introducing the plate geometry shown above in black and yellow on top of a temperature field obtained from a model incorporating a pair of symmetric plates. As a result, the mantle flow reorganizes. However, in contrast to models that do not include oceanic plates, the hottest regions of the mantle (indicated by the dark isosurface) persist below the large oceanic plates.

a)

GEMLAB 2 (1100 km)

b)

GRAND 1997 (1000 km to 1150 km)

CASE 232 RHEOLOGICAL PLATES
VISC: 1000X LID, 1000X LM
YLDSTRS=130 MPA ESTAR=90
19 JULY 1999

LOG VISCOSITY

TIME = 4.000E+09 YR
EQUATORIAL SECTION
ZERO LONGITUDE AT BOTTOM
MAXIMUM VELOCITY = 1.484E+01 CM/YR

Dynamic Surface Topography, $L=1-8$

Crust 5.1 Inference

Theoretical Prediction

Plate geometry, bird's-eye view.
Continent shaded in yellow.

a: $t=0.00$

d: $t=0.025$

b: $t=0.005$

e: $t=0.035$

c: $t=0.015$

f: $t=0.045$