N91-21595

SECTION VI.

REPORT OF THE PANEL ON EARTH STRUCTURE AND DYNAMICS

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SECTION VI.

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SUMMARY

The panel has identified problems related to the dynamics of the core and mantle that should be addressed by NASA programs. They include (1) investigating the geodynamo based on observations of the earth's magnetic field, (2) determining the rheology of the mantle from geodetic observations of post-glacial vertical motions and changes in the gravity field, and (3) determining the coupling between plate motions and mantle flow from geodetic observations of plate deformation; we also stress (4) the importance of support for interdisciplinary research to combine various data sets with models that couple rheology, structure and dynamics.

Core Fluid Dynamics and the Geodynamo

Fluid motions of the Earth's liquid outer core, an electrically conducting liquid, maintain Earth's main magnetic field against ohmic dissipation by a self-sustaining dynamo process. Those motions also cause a variety of time-dependent geomagnetic phenomena, such as an apparent slow westward drift of the non-dipole field, occasional short-term changes in the rate of geomagnetic secular variation (called magnetic impulses, or jerks), and sporadic, but geologically rapid excursions and reversals of magnetic polarity. This dynamo, one of but many in the universe, is special in that it can be probed up close and, in principle, for long duration.

To view a hydromagnetic dynamo is to see a fluid motion with the magneto-regenerative property, so an outstanding issue in core geophysics is the inversion of geomagnetic data for core fluid motion. As it stands, this inverse problem, even for surface fluid motion just beneath the core-mantle boundary, is highly non-unique (and non-linear), so dynamical assumptions are needed. The fluid motion has been presumed to be either purely horizontal, temporally steady, or in geostrophic balance. A variety of possible surface fluid motion patterns have thereby been derived which fit the geomagnetic data.

Such patterns can also be used for estimating a pressure torque on core-mantle boundary topography. This effect may explain decade fluctuations in the length-of-day, and these same motions certainly contribute to the delivery of convective heat flux from the upper core towards the core-mantle boundary. On the other hand, the electrical conductivity of the D" layer and lower mantle may be sufficient to electro-magnetically couple core fluid motions with the mantle, thus accounting for the decade-scale length-of-day changes. Clearly, the resolution of this issue has interdisciplinary aspects.

For such studies, the geomagnetic secular variation rate, at the core-mantle boundary, is as important as the main geomagnetic field itself. To time-differentiate the data, it becomes essential to obtain long-term, global, continuous geomagnetic field measurements. A decade of such observations from near-Earth satellites therefore remains of highest priority.

We recommend that NASA measure the three components of the vector geomagnetic field to one nanotesla accuracy in each component with global coverage from an altitude of 600 km or more and for a duration of at least one decade.

Because the Earth's outer fluid core is a contained rotating fluid, it possesses multiply infinite suites of free modes of oscillation. The simplest of these, which is a nearly rigid-body wobble of the fluid core relative to the mantle, may be responsible for an anomalous retrograde annual term in the VLBI nutation observations. The period of the mode differs fractionally from the sidereal period by the order of the ellipticity of the core-mantle boundary. VLBI observations have been used to estimate a non-hydrostatic deviation of the shape of the core-mantle boundary of the order of 5%. Continued advances in improving VLBI measurement accuracies are needed to complement theoretical progress in core dynamics research. In addition, superconducting gravimeters which seem to hold the most promise for the detection of other members of the suites of core oscillations would provide very useful corroboration of VLBI results and better vertical control if installed at the same sites as the telescopes. We therefore recommend such deployment at a selection of globally-distributed VLBI sites. The direct detection of the principal core mode, called the free core nutation, and the discovery of other inertial modes which reflect details of density stratification in the core, would represent major advances in our understanding of core dynamics and structure.

Mantle Flow and Rheology

The solid earth is actively deforming at all spatial scales. At global scales, viscous rebound in response to the most recent episode of Pleistocene deglaciation may be the dominant contributor to this deformation. Current models of mantle rheology are based on geologic observations of this rebound, and are consistent with observations of slow changes in the lowest zonal coefficients of the earth's gravity field. By making global, geodetic observations of this ongoing deformation we can greatly increase our knowledge of the rheological structure of the mantle. We therefore recommend developing a capability to measure vertical surface motions associated with these deformations at millimeter precision over spatial scales of 1,000 to 10,000 km. More importantly, we recommend a long-term program to monitor concomitant temporal changes in the gravity field. This will confirm if the changes in the second zonal harmonic of the field that have been detected already in the LAGEOS satellite ranging data are indeed due to post-glacial rebound. Passive satellites similar to LAGEOS should, as a first priority, be employed to make these observations at long wavelengths (degree <8). High-precision, low-elevation, gravity field satellites such as SGGM could provide useful temporal observations at shorter wavelengths. These observations of vertical motion and gravity are also essential for interpreting motions resulting from the melting of the sheets and changes in sea level. The post-glacial rebound problem is intimately linked to that of global change.

Plate deformation

Motion of tectonic plates is a direct manifestation of mantle flow. At the same time the relative rigidity of the plates shield smaller scale motions from view. Deformation of plates, however, will reflect the stresses acting on the plates by underlying flow patterns. Measurement of relative plate motions will reveal any inconsistencies with plate rigidity. Direct measurement of deformation within plates can reveal patterns of deformation related to mantle flow, and will elucidate the mechanical properties and modes of deformation and fracture of the plates. The long term thermal evolution of the earth depends primarily on the heat transport throughout mid-ocean ridges. The geometry of plates, and hence the length and activity of spreading ridges, depends on how plates form, evolve and reform. Measurement of deformation in a large oceanic plate (the Pacific) and a plate with a possible incipient subduction zone (the Indian plate in the central Indian Basin) will reveal how oceanic plates fail and create new plate boundaries. Measurement of deformation in a continental region (North America) will indicate possible differences in the mechanisms of deformation of continents and oceans, and will bear on mechanisms of growth and evolution of continents. Such studies are essential to understanding how the plates interact with convective heat transport and the evolution of the mantle.

Interdisciplinary Studies and Modelling

Understanding the dynamics of the mantle requires the integration of data from diverse sources with sophisticated modelling and computational capabilities. Gravity (or the geoid) directly reflects density heterogeneities that drive flow in the mantle. At the present the long wavelength field (degree <20) is sufficiently well determined for studies of large-scale flow. Short wavelength gravity (length scales < 500km) only reflects uppermost mantle and lithospheric densities, and together with topography and seismic data, bears on convective instabilities and structure beneath the lithosphere, and small scale lithospheric structure and deformation.

Other data sets bear on the convective evolution of the mantle. Isotopic data from basalts suggest heterogeneities that have existed for a major fraction of earth history, and also reveal the history of differentiation and crustal formation. Most recently, seismic data have revealed mantle heterogeneity that is partly consistent with the gravity field, and appears to reflect temperature or compostion fields related to flow. No single data set is complete or detailed enough to determine the flow and evolution of the mantle; rather models must be generated and tested against seismic, geochemical, plate motion, seismicity and deformation data. This requires treating a variety of data, and reducing basic data (e.g. seismic travel times) in terms of models constrained by other observations, such as plate motion and the history of subduction. Such an approach will require support for group of researchers with expertise and access to the relevant data. Sufficient computer resources, both in terms of speed and ability to treat large data sets, must also be available. At present, numerical models of convection directly relevant to the earth tax the largest computers. Substantial computer power is needed for basic modelling as well as treating large data sets. Development of sophisticated software requires support of trained specialists, working together with geodynamicists.

We also recognize the importance of laboratory and theoretical investigations of the physical properties of earth materials under conditions of high temperature and pressure found in the earth's interior. This data must be incorporated into models of flow and deformation that relate various observational data sets.

RECOMMENDATIONS

1. Monitoring of the earth's long wavelength magnetic field to produce models at 6 month intervals (or shorter). This to be done with satellite measurement of the vector field to an accuracy of 1 nT. in each component for at least a decade.

2. Measure secular changes of the earth's gravity to detect post-glacial rebound and changes in ice volume and sea level. This could be done with STARLETTE/LAGEOS style passive satellites or a long lived (>3 years) SGGM mission. The minimum required spatial resolution in the zonal harmonic coefficients is degree less than 8 and the required sensitivity is 10^{-12} per year.

3. Deploy superconducting gravimeters at globally distributed VLBI observatories in order to detect gravity changes caused by the internal dynamics of the core. This will also contribute to determination of vertical motions and polar motion.

4. Develop capability to measure secular motion (horizontal and vertical) as small as 1 mm per year in order to detect current post-glacial rebound and motions related to sea level variations.

5. Measure deformation within tectonic plates, with emphasis on intraplate deformation related to underlying mantle flow, and the ultimate appearance and disappearance of plates or plate boundaries.

6. Support interdisciplinary studies and analysis of related data sets (seismic, gravity, rotation, etc.) ; such data should be made accessible to the wider community. This should be done by support of research groups, including post-doctoral researchers.

7. Support modelling of dynamical processes in conjunction with analysis of relevant data sets through the provision of super-minicomputers (e.g. 10's of Mflops) for research groups, as well as access to supercomputers.

INTRODUCTION

The major questions considered by this panel dealt with strategies for improving knowledge of Earth's deep interior, from the highly conducting magneto-hydrodynamic fluid core, to the viscously convecting mantle. We were particularly interested in understanding how boundaries of the mantle interact with units below and above and transfer stress and heat. The major themes are therefore 1) study the hydrodynamo by observing Earth's evolving long wavelength magnetic field using a high altitude and long-lived, orbiting spacecraft; 2). Determine the rheology of Earth's mantle, especially its vertical structure from a campaign to measure both vertical crustal motions and secular changes in the long wavelength gravity field resulting from post-glacial rebound and; 3) determine the coupling between plates and mantle flow from geodetic observations of mantle deformations. We also stress the interdisciplinary nature of this research and request augmented support for both innovative research and improved analysis tools.

The pressing scientific issues discussed in this report are broken up according to both Earth structural units and measurement strategies. We begin by discussing core dynamics and end by looking at how the Earth relates to its sister planets and our moon.

LONG TERM FLUID CORE FLOW AND THE GEODYNAMO

The most obvious manifestation of the Earth's fluid core is the presence of a primarily dipolar magnetic field at Earth's surface . The apparent dipole axis is tilted by about 11° and presently moves at a rate of approximately 0.05°/yr. The non-dipole field shows drifts and motions on the order of 10's of kilometers per year or 1 millimeter per second. This dynamic behavior was probably the first indirect demonstration that Earth is not entirely solid. If the field observed at the Earth's surface is extrapolated to the core-mantle boundary, the magnetic field becomes much more complex and displays patterns which may be related to upwelling and downwelling fluid and the interaction with core-mantle topography.

The electrical conductivity of the fluid core is of the order of 3×10^5 s/m, while that of the mantle is at least 10^3 smaller. The drift of magnetic field lines with respect to the core fluid is much slower than the fluid velocities themselves (mm/sec). Magnetic field lines are effectively trapped on convective time scales and are stretched, sheared and compressed in a complicated fashion as part of the hydromagnetic process. This phenomenon, though not an entirely understood process, transfers energy back into the magnetic field so that, while it would otherwise decay by ohmic dissipation, it becomes regenerative. Since the convection itself is probably chaotic, this process is not steady. Occasional short term changes in the core field are characterized as "jerks" with time scales as short as a year. The paleomagnetic record reveals that the dipole character itself, and its average inclination to the rotation axis, appear to be maintained for time scales as long as 10^5 to 10^6 years, then suddenly change on time scales as short as 10^3 years and may reverse direction. The resulting record of seafloor magnetic lineations with reversed polarity was the first widely accepted evidence for plate tectonics.

As just described, to view the hydromagnetic dynamo is to see a fluid motion with the magneto-regenerative property. An outstanding issue in core geophysics is the inversion of geomagnetic data for the core fluid motion. As it stands, this inversion problem, even for surface fluid motion just beneath the core-mantle boundary, is highly non-unique (and nonlinear), so dynamical assumptions are needed. The fluid motion has been presumed to be either purely horizontal, temporally steady, or in geostrophic balance. A variety of possible surface fluid motion patterns have thereby been derived which fit the geomagnetic data.

Such patterns can also be used for estimating a pressure torque on core-mantle boundary topography. This effect may explain decade scale fluctuations in the length-of-day, and these same motions certainly contribute to the delivery of convective heat flux from the upper core towards the core-mantle boundary. On the other hand, the electrical conductivity of the D" layer and lower mantle may be sufficient to electromagnetically couple core fluid motions with the mantle, thus accounting for the decade-scale length-of-day changes. Clearly, the resolution of this issue has interdisciplinary aspects.

For such studies, the geomagnetic secular variation rate, at the core-mantle boundary, is as important as the main geomagnetic field itself. To time-differentiate the data, it becomes essential to obtain long-term, global, continuous, geomagnetic field measurements. A decade of such observations from near-Earth satellites therefore remains of highest priority.

SHORT TERM FLUID CORE DYNAMICS

Of the three fluid domains of the Earth, the outer core is by far the least accessible to observation. Like the oceans and atmosphere, its dynamics is dominated by the Coriolis effect arising from planetary rotation. At longer periods, months and greater, the fact that the outer fluid core is the seat of the geodynamo, responsible for the main magnetic field and the other phenomena just described, vastly complicates its dynamical behavior compared to its geophysical fluid sisters, the oceans and atmosphere. At shorter periods, less than months, the Lorentz interaction between the motion and the magnetic field and its supporting currents is fortunately negligible, and a purely mechanical description of core dynamics is possible, providing a window on core dynamics free of the complications of hydromagnetism.

We may therefore view the outer core at shorter periods as a rotating, self-gravitating fluid mass contained between the elastic boundaries provided by the mantle and inner core. Studies of the dynamics of such bodies have their roots in the classical literature of the nineteenth century. In this century, our knowledge of the general properties of rotating fluids has been greatly extended by laboratory experiments and theoretical and computational work .

It is known that the outer core possesses free modes of oscillation with periods which, in the simplest model, are bounded below by half the rotation period. At least one of these modes is capable of exchanging equatorial angular momentum with the mantle and is referred to as the 'free core nutation' because it is very nearly a rigid-body motion of the whole outer fluid core. Neglecting the finer details of realistic Earth structure, its period depends on the shape of the core-mantle boundary.

The anomalous resonant response arising from the free core nutation has been seen in both the records of observatory gravimeters and in VLBI nutation measurements which reflect, respectively, the response to diurnal tidal deformation and nutation. These observations have been interpreted to infer a flattening of the core-mantle boundary which differs from the hydrostatic value by 6%. Thus, we appear to be on the threshold of a new observational era in core dynamics which promises to improve observational accessibility to the core and its structure.

The question of whether or not there are other core modes in the real Earth that can exchange angular momentum with the mantle and crust, and are therefore susceptible to observation by the VLBI technique, is the subject of current research (Smylie, 1989). Should such modes exist and be observable, it is expected that they would be much more diagnostic of the details of core structure than the free core nutation, which to first approximation, is a bodily motion of the whole core. The direct detection of the free core nutation has yet to be confirmed, only an associated anomalous annual retrograde nutation has been unequivocally observed. Presently an upper bound of 0.3 milliarcseconds has been obtained. The continued evolution of the accuracy of the VLBI technique is thus of prime importance in core dynamics.

Core modes that do not exchange angular momentum with the mantle and crust should still provide a gravity signal that is close to the observational levels being reached by gravimeters using the levitation of the proof mass in the field of a superconducting magnet. Indeed, there have been reports in the literature of such observations already having been made. Unfortunately, these results are based on only one superconducting gravimeter record and a network of such instruments is required to eliminate the possibility of local oceanic basin modes or other spurious signal sources.

The detection of these modes would lead to much more precise determination of the density stratification of the fluid outer core than is possible by known seismic or other methods. This parameter is crucial to our understanding of the dynamo mechanism and heat and mass transfer in the core. Gravimeters also allow the measurement of local station tidal response and they sense polar motion, complementing VLBI records. Transient tectonic, atmospheric or climatic stochastic events which might displace the stations vertically, and therefore change gravity, will be observable by both the VLBI network and the collocated gravimeter. In fact, on terms less than a year in length, superconducting gravimeters are much more sensitive to vertical motion than the VLBI technique. This linked system will produce both complementary signals and corroborating evidence for real events which otherwise might be discounted. This type of relative gravimeter, although much more stable than other instruments of the relative type, is not appropriate for detecting very long term secular motions, such as those associated with glacial rebound. For this purpose, the strength of the VLBI technique is the fact that it is tied to a nearly absolute inertial reference frame (the quasar reference frame).

Convection within the fluid core is either driven by bouyancy resulting from the slow growth of the inner core as nearly pure iron freezes out of the alloyed iron mixture, heat sources within the inner core or fluid core, or lateral temperature variations across the core-mantle boundary. Of these options, the first appears most plausible, although it depends to some extent on the density contrast at the inner core boundary.

Earth nutations and wobble may be affected to a small extent by the density contrast, due to the resonant response of the inner core to forced wobble and nutation of mantle. The inner core itself has free rotational motions, similar to that of the mantle and the fluid core. Detection of these free modes or their influence on forced nutations may place constraints on the density contrast between the inner and outer core and the topography of the core mantle boundary.

THE CORE-MANTLE AND D" BOUNDARY

The 200 to 300 km thick transition zone, or D" layer, at the base of the mantle plays a profound role in mediating convective transfer of heat from the core to the mantle. The style of mantle convection, thermal and chemical plume formation and evolution, core fluid convective patterns, and hydromagnetic field generation, may very well depend on the chemical, thermal, rheological, and electrical properties of the D" layer as well as its lateral variation in vertical structure (Lay, 1989). High pressure laboratory studies have led to improved understanding of the physical properties of the outer core and lower mantle materials during the last decade. Perhaps the greatest advance has resulted from the examination of large suites of seismic travel times to search for systematic signatures caused by lateral mantle structure and core mantle topography using the tomographic technique.

The tomographic analysis of up to 10^6 P wave residuals and free oscillation frequency shifts have been extended to the core mantle boundary. These analyses reveal large (approximately 1 to 2%) velocity variations near the boundary and were initally interpreted in terms of excess topography of order 3 to 10 km peak to peak (Hager et al., 1985; Morelli and Dziewonski, 1987). As already discussed, comparison of hydrostatic models for forced nutation of Earth's spin axis with the observed periodic signature reveals a 2 milliarcsecond anomaly in the retrograde annual term (Herring et. al., 1986). The estimated accuracy of this measurement is now better than 5%. Neither errors in ocean tide models or atmospheric thermal tides could account for this effect. Although it might be due to the presence of other members of a suite of free core nutations which are yet undiscovered, the most compelling explanation is that the core-mantle boundary has an excess second harmonic ellipticity of 6%, equivalent to a 0.5-km increase in the equatorial relative to the polar radius. Analysis of gravimetric diurnal tidal signatures, although less accurate, appear to support this interpretation. The core-mantle boundry could have large, average topography in which the mean ellipticity is small (Morelli and Dziewonski, 1987). However, recent attempts to explain decade-scale changes in length of day (lod) in terms of momentum exchange at the core mantle boundary appear to require only 0.5-km scale core-mantle boundry undulations, in agreement with the nutation result but in conflict with simple seismic models of this boundary. This calculation uses temporal changes in the long wavelength magnetic field to infer the fluid velocity field at the core-mantle boundry. This calculation employs the frozen flux approximation and assumes a source-free, insulating mantle. Seismic tomography still provides the core-mantle boundary topographic structure, while the scale is determined by matching the observed 4-msec lod change with the predicted change from their model. The model employs a mountain torque approach to estimate the torque arising from a lateral pressure force caused by fluid motion across the topography. This calculation appears to rest on a series of complex models and neglects the possibility that electromagnetic interaction of the magnetic field with a highly conducting D" layer might account for part or all of the lod change. Nevertheless, these kinds of interactions have focused attention on D" vertical structure. Undulations at the top of D" may very well account for the seismic anomaly.

The existence of a distinct, and perhaps dynamically unstable, thermal boundary at the base of the mantle is predicted from theoretical models of mantle convection with a temperature sensitive viscosity. Early seismic evidence for the layer came from increased radial velocity gradients at the base of the mantle. Tomographic models exhibit large lateral variations in seismic P and S wave velocity, compared with the middle mantle. Precursors to the reflected S and P waves have been observed in some isolated patches of D" (Lay, 1989). Whether these represent a reflection at a density jump at the top of D" or lateral heterogenity in D" is uncertain. The patches with observed precursors correlate with long wavelength, high-velocity P wave tomographic anomalies, while the D" top is not seen in the Pacific, which corresponds to a low velocity P wave region.

The temperature contrast across the D" layer may be greater than 700^{o} K based on the estimates of the minumum outer core temperature of 3800^{o} to 4700^{o} K. The core temperature range depends on whether sulphur (lower) or oxygen (higher) is the primary alloy component. The lower mantle adiabat is in the range 2600^{o} to 3100^{o} K. The melting point of perovskite at core-mantle boundry pressure is about 3800^{o}K, so that "D" may be near the solidus and contain significant partial melt. Small-scale heterogeneity of order 5% has been inferred from analysis of scattered P wave phases (Bataille and Flatte, 1988). Small-scale convection within the layer itself may occur. High pressure experiments indicate that Fe is highly reactive with silicates at core-mantle boundry pressure, but it is unclear whether this reaction extends more than a few hundred meters above the core-mantle boundary. The importance of this process is that it could increase electrical conductivity within D" by 10^4 .

DEEP MANTLE CONDUCTIVITY

The conductivity of perovskite and by extension the mid-mantle is not well determined, with laboratory values ranging from 10^{-2} s/m to 10^{2} s/m. Its value also depends on the fraction of iron assumed for mantle composition. The 1969-1970 geomagnetic jerk may have occurred on a time scale as short as 1 year. However, the equivalent event at the core-mantle boundary may have occurred a decade earlier, if a similar event in Earth rotation is related to this magnetic jerk. Future space missions carrying magnetometer instruments to study the main field should strive to attain enough data to solve for magnetic field maps, perhaps every 6 months and on a regular basis. Capture of the onset of the next jerk could resolve many phenomena relating hydromagnetic "weather" and mantle electrical properties.

Several different approaches to this problem deserve support. High pressure laboratory experiments on appropriate mineral assemblages with both shock waves and heated diamond anvil presses hold promise for reaching the required range of pressures (about 80 to 130 GPa) and temperature (2000-5000^{o} K). Long-term monitoring of the geomagnetic poloidal field may reveal magnetic impulses or jerks, whose diffusion through the mantle can constrain some weighted integrals of the conductivity, provided diffusion time-scales can be established by linking the onset of a jerk with a corresponding feature in the length-of-day data. Monitoring of the diffusion of the external field caused by the 22-year solar cycle provides additional constraints, especially on the upper mantle. Further theoretical studies are also needed because the electrical conductivity is closely associated with another important unknown quantity, the toroidal magnetic field in the mantle, which could be 10^{2} larger than the poloidal field there. The toroidal magnetic field in the deep-mantle, as it diffuses into the mantle from below, generates currents and electromagnetic torque, changing Earth's rotation. Comparison of the estimated electromagnetic and pressure induced torques inferred from magnetic field variations and core mantle topography, can be compared with the long term length-of-day changes to infer diffusion time scales, bulk mantle conductivity and toroidal field strength.

In addition, mantle conductivity may serve as a proxy for temperature and thereby determine the geotherm. Knowledge of the geotherm could contribute to our understanding of the relative importance of chemistry and thermal expansion on variations in density with depth.

The Earth's mantle is a convecting system that transports heat from the interior to the surface. Some heat comes from within the mantle, from radioactive heat sources and from whatever secular cooling is occuring, and the rest comes from the core beneath the mantle. Heat from the core may come from radioactive decay, but more likely results from cooling. As the core cools, the solid inner core crystallizes from the liquid, releasing latent heat of crystallization. In addition, the precipitation of solid iron from the liquid outer core (which contains a lighter component) will result in an enrichment of the lighter component near the inner-core boundary. This light fluid wil be unstable and will flow upwards thereby displacing denser fluid. This process effectively converts gravitational potential energy into fluid motion and ultimately into heat.

The existence of the Earth's magnetic field requires a source of energy in the core where it is generated, which implies that some heat must be flowing into the base of the mantle. Estimates based on the ohmic dissipation of electric currents in the core suggest that the total heat flow from the core may be as large as 10 to 20 percent of the heat flow at the Earth's surface. If it is this large, the heat flux (per unit area) at the two boundaries would be of similar magnitude as would convective heat transport. Nevertheless, the bulk of the Earth's heat flow originates in the interior of the mantle.

The most obvious manifestation of mantle convection is the motion of tectonic plates on the surface. The plates comprise the thermal boundary layer of the convecting system, through which heat is transported by conduction. The temperature drop across this layer is around 1200 degrees C, based on the temperature of magmas that are erupted to the surface. Beneath this layer the temperature should be more or less adiabatic, with non-adiabatic variations that drive convective motions and heat transport. At the base of the mantle there should be another boundary layer, associated with heat flow out of the core. A nonadiabatic temperature difference will exist across this layer as well, but its exact magnitude is so far undetermined.

The boundary layer at the Earth's surface has particular characteristics, primarily owing to the extreme temperature dependence of the mechanical properties of earth materials. Because the layer is so much colder than the material beneath, it is much more resistant to deformation and forms a number (twelve or so) of essentially rigid plates that are in relative motion reflecting the convective motions beneath. The boundaries between the plates are not rigid at all but are zones of concentrated deformation which are relatively quite weak. These plates comprise a mechanical boundary layer, the lithosphere, as well as a thermal boundary layer. Where two plates diverge, hot material wells up from the interior, advecting heat to the surface. Where plates converge, material that has cooled off at the surface sinks back into the interior, where it cools off the surrounding mantle. The sinking boundary layer is apparent as the locus of deep earthquakes that occur as the strong, cold boundary layer is deformed. These provide the only direct evidence of the path of material within the mantle.

Where plates diverge, molten lava rises to the surface and forms a six kilometer thick layer of oceanic crust, which appears to form in the same fashion and with similar properties at all divergent boundaries. The magma, which probably forms by partial melting at around 50 km depth, transports heat to the surface very efficiently, and also heats the surrounding material to a uniform temperature from which it cools by conduction as the the plate moves away from the boundary. The plate subsides as it cools and contracts, and the resulting decrease in elevation (proportional to the square root of the age of the plate) is observed and confirms the hypothesized process of conductive cooling. By around 100 million years a plate will have cooled to a depth of around 80 km. Eventually it sinks into the interior at a convergent boundary.

Spreading at divergent boundaries is always symmetric (or nearly so), so that new material is added to both plates at the same rate. In contrast, convergent boundaries are asymmetric, and only one plate sinks and is destroyed. As a consequence, the geometry and sizes of the plates are continuously changing as some plates grow while others shrink and ultimately disappear. A representative average lifetime for a plate is around 200 million years at present rates of plate motion. If no new plates were formed the number of plates would decrease until only one were left; thus new plate boundaries must form to create new plates in order to sustain the process. At present, we do not know how, where or why new plate boundaries form, only that they certainly have in the past and most certainly will in the future.

Although the oceanic parts of lithospheric plates appear to be rigid, the geologic history of continental parts presents a record of substantial deformation Furthermore, some regions (e.g. the Himalaya, the western U.S) are actively deforming now as evidenced by seismic activity and landforms such as recently uplifted mountains. An explanation for this is that the thicker continental crust (40 km or so) prevents the material in the upper mantle from becoming cold enough to be as strong as oceanic upper mantle, which is overlain by only 6 km of crust. The crustal material is relatively weak, and contributes little to the strength of the plate. Certainly some spreading ridges initiate in continents, as did the mid-Atlantic ridge that separates North America and Africa. Other ridges have intiated in oceanic lithosphere such as several in the western Pacific. But the creation of a new plate also requires the formation of a new subduction zone, and we have no evidence of how or where they form.

The variable geometry of plates affects the rate of heat flow of the Earth. Most of the heat flow is near spreading ridges, where hot material is close to the surface. Changes in plate geometry that substantially change the total length of ridges on the Earth will correspondingly change the heat flow. At present we do not know how much the Earth's total heat flow was varied, nor do we know how representative the current value (41 TW) is of the long term average. The history of the plate system needs to be well known in order to know the thermal history, and more importantly, the mechanism of plate initiation must be known in order to understand how the plate system and thermal state of the Earth evolve.

The fluid mechanics of the flow in the mantle is characterized by several dimensionless numbers: the Reynolds number is essentially infinitesimal, which means that inertia is unimportant and the forces driving flow are resisted by viscous stresses; the Prandtl number is essentially infinite, which means that viscous stresses are transmitted essentially instantaneously through the whole fluid, while thermal effects are only felt locally. The rate of convection is characterized by the Rayleigh number, which has been variously estimated from 10^6 to 10^9 depending on the depth of the layer that is convecting. These estimates depend on the surface heat flow, which is reasonably well known, the depth of the convecting region, which is taken to be either the entire mantle (3000 km) or the upper mantle (700 km), and various physical properties of the material, the most uncertain of which is the viscosity.

Estimates of the viscosity of the mantle come primarily from observations of the rebound of the Earth's surface following the melting of the Pleistocene ice sheets; these are primarily uplifted shorelines in North America and Europe, as well as some other regions that reflect motions in response to the increase in sea level. Models of this process have estimated the radial variations of viscosity, and also indicate that vertical motions of the order of millimeters per year may still be occuring. There are still considerable uncertainties about the models, however. Most of the data comes from near the glaciated regions; since these happen to be continental shields (of great geologic age) the mantle beneath may not be representative of the entire mantle. In particular, the mantle beneath oceanic ridges where upwelling occurs should be hotter and perhaps considerably less viscous. Observations of secular changes in the Earth's rotation rate and changes in the shape of the Earth (expressed in the long wavelength gravity field) have also allowed estimates of the average viscosity. These are grossly consistent with the others, but the the absence of any spatial resolution makes comparisons relatively uncertain. Measurement of current uplift and determination of its spatial distribution would greatly increase our knowledge of the rheology of the mantle, which is essential for predicting vertical motions of the surface associated with long term loads such as changes in sea level, as well as for understanding convection and deformation in the Earth's interior.

Numerical models can at present treat some aspects of mantle convection, but there are severe limitations. The length scale of temperature variations in the mantle is dictated by the thickness of the thermal boundary layer on the surface. This is, on average, around 30 km, which is then the spatial resolution needed in a numerical model. For uniform coverage of the mantle, this would require a grid of 10^8 points, which is well beyond the capacity of the largest computers. The simulation of processes associated with partial melting and the formation of oceanic crust would require even more resolution. Thus, simulation of convection in the mantle is clearly impossible at present (and even for the forseeable future), and one must identify specific problems that are tractable and will shed light on particular aspects of the convective processes.

Observations of mantle convection, apart from plate motions, must be indirect: the near rigidity of the plates shields the upper mantle from view. Variations in density related to temperature variations (which drive the convective flow) cause variations in the Earth's gravity field; however these are detectable only within distances comparable to a few times the scale of the heterogeneities. Thus only the larger scale components of the density field in the deeper mantle are apparent beyond the surface. These large scale components may be averages over a smaller scale structure, and may represent only a part of the structure associated with convection in the mantle.

The most direct observations of the interior of the mantle have come from seismology: the inversion of travel times of seismic waves has yielded models of three dimensional seismic velocity variations in the mantle. The long wavelength components of this structure can be related to the lower degree components of the gravity field. Assuming that the seismic anomalies represent density anomalies as well, one can calculate the resulting effect on the gravity field. This yields a good comparison only if the mantle is assumed to be fluid (rather than strictly elastic), and in addition constrains the radial variations of viscosity. A further constraint comes from assuming that the seismic anomalies represent temperature variations. The resulting density variations drive flow in a viscous medium, thereby advecting heat. For this heat flux to be less than that at the Earth's surface places an lower limit on the ratio of the viscosity and the temperature variations [Hager and Clayton,1989].

More detailed tomographic studies hve been conducted for regions near subduction zones, and in the western U.S. These have revealed smaller scale features associated with the sinking of parts of the cold lithospere into the mantle. The detail achieved is only possible at present in regions with a dense array of seismometers, such as Japan and the western U.S. The development of portable seismic arrays will allow the extension of such studies to other areas of interest, such as regions of continental convergence or extension.

MANTLE RHEOLOGY

Background

In order to understand and model the exact manner in which the "solid" Earth, i.e., the mantle and crust, convect, it is essential that we know the consitutive or rheological laws which relate strain rate to stress. Regional geophysical and geological studies in conjunction with laboratory experiments have yielded rough estimates of viscosity for limited portions of the crust and upper mantle. Indeed, we know that outermost layer of the solid Earth - the lithosphere - is highly resistant to flow. Geological studies in conjunction with laboratory experiments have yielded rough estimates of the effective viscosity for limited portions of the crust and upper mantle . However, for the bulk of the mantle, particularly, the deep mantle, we have only a lumped estimate of viscosity (~4 x 10^{21} Pa s). This estimate was derived by detailed modelling of the ongoing viscous rebound of the solid Earth occurring in response to the last global deglaciation (of Wurm-Wisconsin ice) which began 18,000 years ago and largely ceased 6,000 years ago.(see Wu and Peltier, 1983; 1984) This modelling has been primarily constrained by geological observations of relative sea level (i.e., uplifted shorelines). Additional constraints include an apparently associated secular change in the second zonal harmonic of the gravity field (Yoder et al., 1983; Rubincam, 1984) of approximately -3 x 10^{-11} per year; this result is consistent with earlier inferences based on non-tidal secular changes in the length of day.

However, these existing constraints are not, by themselves, sufficient to do that which is needed, namely, a spatial mapping of the rheological structure of the mantle. Hager (1984) has inferred from models of gravity anomalies and subduction dynamics that large radial variations in viscosity may exist within the mantle. Seismic tomography implies that significant lateral variations of viscosity also exist. To begin mapping the rheological structure of the mantle, we need to begin a long-term program of precise, global geodetic observations of this ongoing postglacial rebound and associated processes.

DETECTION OF POST-GLACIAL CHANGES IN GRAVITY FIELD FROM PASSIVE SATELLITES

The zonal harmonics of the gravity field are symmetric about the polar axis and cause long periodic changes in the shape and spatial orientation of the orbit. The even zonal coefficients drive the precession of apse and node of a satellite. If the orbital inclination is high, the odd zonal coefficients induce an additional eccentricity-like orbital displacement.

The secular change in the second harmonic coefficient J_2 was initially observed through its effect on Lageos. This rate was confirmed more recently by analysis of three years of Starlette data. (Schutz et. al., 1989). In addition to a rate for J_2 of $-2.5 \pm 0.3 \times 10^{-11}$ yr, they obtain rates for J_3: $(-0.1 \pm 0.3 \times 10^{-11}$ yr) and for J_4: $(0.3 \pm 6) \times 10^{-11}$ yr^{-1}. If the signal is due to rebound, then the J_3 rate should be relatively small because of nearly equal contributions to rebound from Northern Canada and Antarctica for this term. However, simple models predict that the J_4 rate should be near -1 x 10^{-11} and it is not yet clear if the observations are in conflict.

Present day melting of glaciers also contribute to secular change in gravity and cloud this simple interpretation. However, this component could conceivably be accounted for if runoff or ice-packs were closely monitored. As the harmonic number or degree is increased, the strains associated with that deformation is concentrated towards the surface. The relaxation of each harmonic order is therefore governed by the vertical distribution of viscosity. Measurement of a low order suite of zonal harmonic coefficients could be inverted to obtain a radial viscosity profile. The zonal harmonics of degree ≤ 8 should suffice, given that Antarctica is enclosed within a nodal line of this spherical function. The ability to discriminate between various models requires an accuracy of about 10% or 20% or an uncertainty in J_n rate of roughly $\pm 10^{-12}$ /yr for low degree n. The proposed Stella and Lageos II missions should improve the secular gravity field determination. However,the orbital characteristics for these proposed satellites have not been chosen to improve the solution for the low order zonal harmonics . We therefore recommend that orbit design for future missions place high priority on zonal field resolution. This requirement may be satisfied by a combination of both ranging system upgrades and orbit adjustment. This strategy will also improve the solution for both tidal gravity contributions and the seasonal changes related to redistribution of air mass and groundwater.

The detection of tesseral gravity harmonics is much more difficult. Resonant satellite orbits must be chosen in which the orbit period is nearly a multiple of the day, such that longitudinal features on the Earth appear to move slowly with respect to the satellite. The most significant terms to sample correspond to the C_{22} and S_{22} coefficients, which are doubly periodic in longitude, and the singly periodic C_{31} and S_{31} terms. The former is important in that it will complete the second harmonic field (given that C_{21}/S_{21} can be sensed from the secular polar motion) and determine if its orientation is that predicted from ice sheet models. It could happen that lateral viscosity variations shift the pattern. The C_{31}/S_{31} term is especially important in that Antarctica; because of its polar symmetry it contributes very little to tesseral harmonic coefficients. The detection of this particular term could aid in better constraining the viscosity profile.

The maximum along-track acceleration in a nearly synchronous orbit is $\sim 2 \times 10^{-14}$ m/sec^2 if C_{22} is suddenly changed by 0.25×10^{-12}. Thus detection of this small, but secular signal requires accurate modelling of drag forces; drag can be partially inferred from the along track displacement. However a better method would be to launch two satellites in similar orbits with different area to mass ratios.

Suppose a satellite is initially stationed just below synchronous orbit so that it circulates with respect to points on Earth's surface every 600 days. Assume the orbit is circular and coplanar with Earth's equator to minimize perturbations from other effects. The C_{22}/S_{22} coefficiants would drive a 300 day, 2700 km oscillation along track. A C_{22}/S_{22} change of 0.25×10^{-12} would change the amplitude of this oscillation by about 40 cm. Lageos and Starlette orbit models have achieved fits which equal or surpass this value. Thus it appears feasible that the technique could be used to detect the C_{22}/S_{22} rates and the C_{31}/S_{31} rates as well. The detection of secular rates of other tesseral harmonic coefficients requires additional satellites in a variety of resonant orbits and orbit inclinations and eccentricities. The proposed first mission provides an excellent start.

The primary purpose for launching either a drag free, gradiometer instrument in low earth orbit (150 to 200 km. altitude) or a laser tracked, dual satellite system is to obtain a complete map of the Earth's gravity field with a spatial resolution of around 150 km. and sensitivity of a few mgals. The dual satellite system appears to have sufficient sensitivity at longer wavelengths such that it could detect rebound and other time-dependent changes in gravity with higher spatial resolution than could be achieved by tracking passive satellites. However, the proposed mission lifetimes of about 6 months severely limit their usefulness, given that seasonal mass displacements of air and water will dominate the signal over this period. We propose that a future gravity mission include a high altitude phase (600 km.) lasting from 1 to 3 years in order to avoid this limitation.

TERRESTRIAL OBSERVATORIES

In many earth science disciplines related to the Solid Earth Science Program, ground measurements are necessary, in addition to observations from space. It is proposed that modern, modular terrestrial observatories with a two-way satellite communication link would accommodate various needs of earth sciences as well as measurements in other fields, such as meteorology, atmospheric chemistry or soil properties. The concept of a terrestrial observatory should also be extended to permanent installations on the ocean bottom. Programs such as Global Change and International Decade of Hazards Reduction require a world-wide system of data acquisition, transmission, dissemination, and archiving. The following are examples of ground based measurements related to the Geodynamics Program:

1) Permanent GPS-receiver installations consisting of individual sensors or their arrays connected through a local telemetry system.
2) Volcanological observations.
3) Geomagnetic field measurements.
4) Seismic observations.
5) Gravity measurements with a super-conducting gravimeter.

It is expected that a terrestrial observatory would have a modular design allowing for future expansion or modification of measurements and be equipped with a computer system, or a local computer network, capable of a variety of "intelligent" decisions in addition to routine data reduction tasks, merging of different data streams, and scheduling of individual measurements. Local telemetry could be used in cases when arrays of instruments are used or a common site might be inappropriate for certain subsets of measurements. The stations would have a built-in common recording system using mass-storage media such as large capacity cassettes or optical disks, but the primary mode of data transmittal would be satellite telemetry. The capacity of this system would determine whether all the data or their selected subsets would be transmitted in real time or nearly real time.

Because of the two-way communications, the personnel at a terrestrial observatory could also request data from other stations or other information. In this mode, the role of a terrestrial observatory could be expanded from passive gathering of data to a research and training function. This is particularly important in the Third World countries, where there is the greatest shortage of personnel capable of operating and maintaining sophisticated equipment and where the benefits of co-locating different measuring systems would be most substantial. Integration of observations is, of course, also important in uninhabited locations such as ocean islands or interiors of deserts.

A global observing system requires international cooperation. The International Commission on the Lithosphere recently created a Coordinating Committee for Terrestrial Observatories whose task is to help to establish standards for data collection and exchange.

It is recommended that two or three prototype systems of multi-disciplinary terrestrial observatories with a different mix of measurements be developed and deployed in the United States and that an existing satellite telemetry system be used in the early stages of the experiment. The development of a long-term data transmission, dissemination and archival system should proceed in parallel. It is expected that some 100 globally distributed terrestrial observatories, each generating about 10 megabytes of data per day, will be needed to meet the program objectives. In addition, there is a need to transmit data from simpler, single-purpose measurement systems.

Real-time data transfer requires either dedicated terrestrial communications channels (telephone lines, point-to-point radio links etc.) or channels on geostationary communications satellites. An attractive alternative for low-rate data is the use of low-earth orbit (LEO) satellite store-and-forward communications.

Remote data collection through satellites has been demonstrated using ARGOS, ATS, MARISAT, and other systems. The 400 BPS one-way ARGOS links are the most commonly used.

It would be desirable to design new data collection systems that would enable those responsible for acquiring data during interesting periods to interrogate "smart" remote instruments to supply concentrated data for specific periods. This requires two-way communications.

Recent developments have made it feasible to launch low-cost (<$1 million, including all launch service costs) two-way store-and-forward satellites which work with small, low-cost (<$3000) ground terminals. With such inexpensive systems, it is feasible to dedicate one or more such satellites to special scientific measurement programs.

An example of these satellites are the small "microsat" satellites developed for radio amateurs by AMSAT (the Radio Amateurs Satellite Corp.); the Microsats are 24 cm cubes with 10 kg mass which cost $3-400,000 each. The satellite group at the University of Surrey (VoS) have developed and demonstrated similar techniques with the Digital Communication Experiments (DCEs) on several UoSats.

To launch such small satellites, Arianespace has made available the new ASAP (Ariane Structure for Auxiliary Payloads) which permits up to eight small satellites to "hitchhike" rides with a primary payload. Arianespace has suggested that the cost of including the ASAP and providing "piggyback" launches will be $1 million total -- i.e. < $125,000 per satellite. Four Microsats plus two UoSATS will fly from the ASAP that will be launched with SPOT 2 in November 1989. Other interesting launch opportunities involve the new private launch vehicles (PEGASUS and AMROC) being developed in the United States.

COMPARATIVE PLANETOLOGY

Earth's structure, long term evolution and biological uniqueness in our solar system cannot be completely understood except through studies of other terrestrial planets and their satellites. Presently our knowledge of these bodies is primarily based on surface imagery. For a few of these objects (Mars and Venus), preliminary maps of surface topography and low order gravity models are available. The just launched Magellan mission to Venus is to obtain a global topography map of 90% of its surface, with spatial resolution of 30 km and vertical resolution of 30 m. In fact, this map will be better than anything available for Earth. The mission objective is to obtain a map with sufficient accuracy to determine types of geologic units and, through comparison with similar features on Earth, to infer processes that operate in the interior which control geologic structure and evolution. Comparison of topography with gravity willbe used to infer crustal thickness, dynamic support mechanisms and, in general, answer the question: why does Venus, so similar in so many ways to Earth, appear to be a planet without plate tectonics like those on Earth?

Certainly one major difference is that Earth has a moon and Venus does not. In fact, our moon is even more remarkable in that its mass is comparable to the largest solid moons of the giant planets, whose masses are 15 to 300 times larger. Its relative size, iron compositional deficiency and anomalous tidal history have posed serious puzzles which influence our understanding of how the moon came to coexist with Earth. Although several theories of lunar origin have been posed, the presently ascendant idea is that the moon formed from the debris left orbiting Earth after the impact of a Mars-size body, which occurred late in Earth's accretional history.

If lunar formation did strongly affect the Earth's internal state, then useful constraints on what happened probably can be obtained from information on the lunar interior. The offset of the lunar rotation axis with respect to the Cassini state for an elastic body indicates much higher dissipation of mechanical energy than can be explained from lunar seismic attenuation data and plausible Q values at tidal frequencies. The only likely explanation which has been suggested is the existence of a small fluid core, and dissipation by turbulent viscosity in the core.

Unlike Earth's core, the lunar core mantle boundary is more nearly spherical in shape. In any case, its ellipticity would have to be much larger than 0.004 in order to couple, through a Poincare pressure torque, the precession of the lunar core with the 18.6 year, 1.6^{o} amplitude, precession of the lunar obliquity. The shear at the boundary is almost certainly turbulent, and an estimate of the skin friction has been used to infer a core radius of about 330 km. This couple is probably unsteady and may provide a mechanism for exciting large lunar Chandler-like wobble and periodic length-of-day variations.

This explanation can be tested by looking for fluctuations in the free libration phase and amplitude. If a measurement accuracy of roughly a millisecond can be achieved over a decade period, the presence or absence of changes in the free librations would set fairly tight limits on the rotational torques on the mantle due to core motion. Thus accurate differential range measurements to the different lunar reflectors is recommended.

RECOMMENDATIONS

1. Monitor the Earth's long wavelength magnetic field to produce models at 6 month intervals (or shorter). This could be done with satellite measurement of the vector field to an accuracy of 1 nT in each component for at least a decade.

2. Measure secular changes of the Earth's gravity to detect post-glacial rebound and changes in ice volume and sea level. This could be done with STARLETTE/LAGEOS style passive satellites or a long lived (>3 years) SGGM mission. The minimum required spatial resolution in the zonal harmonic cooefficients is degree less than 8 and the required sensitivity is 10^{-12} per year.

3. Deploy superconducting gravimeters at globally distributed VLBI observatories in order to detect gravity changes caused by the internal dynamics of the core. This will also contribute to determination of vertical motions and polar motion.

4. Develop the capability to measure secular motion (horizontal and vertical) as small as 1 mm per year in order to detect current post-glacial rebound and motions related to sea level variations.

5. Measure deformation within tectonic plates, with emphasis on intraplate deformation related to underlying mantle flow, and the ultimate appearance and disappearance of plates or plate boundaries.

6. Support interdisciplinary studies and analysis of related data sets (seismic, gravity, rotation, etc.); such data should be made accessible to the wider community. This should be done by support of research groups, including post-doctoral researchers.

7. Support modelling of dynamical processes in conjunction with analysis of relevant data sets through the provision of super-minicomputers (e.g. 10's of Mflops) for research groups, as well as access to supercomputers.

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FIGURE CAPTIONS

Figure 1
(a) Magnitude of the radial component of the Earth's magnetic field at the core-mantle boundary obtained by inversion of terrestrial observatory and Magsat data. Much of the time variability of the field is associated with the growth of a 'core spot' off the southeast tip of Africa.

(b) Horizontal velocity field at the top of the core inferred from variations of the magnetic field. This model assumes that the flow is completely toroidal, with no up- or downwelling.(Bloxham, 1989)

Figure 2
(a) Shear velocities in the mantle at depth 1200 km. (Woodhouse and Dziewonski, 1984), determined by waveform inversion of SH waves.
(b) P-velocity in the lower mantle (Dziewonski, 1984), determined from analysis of P-wave travel times.

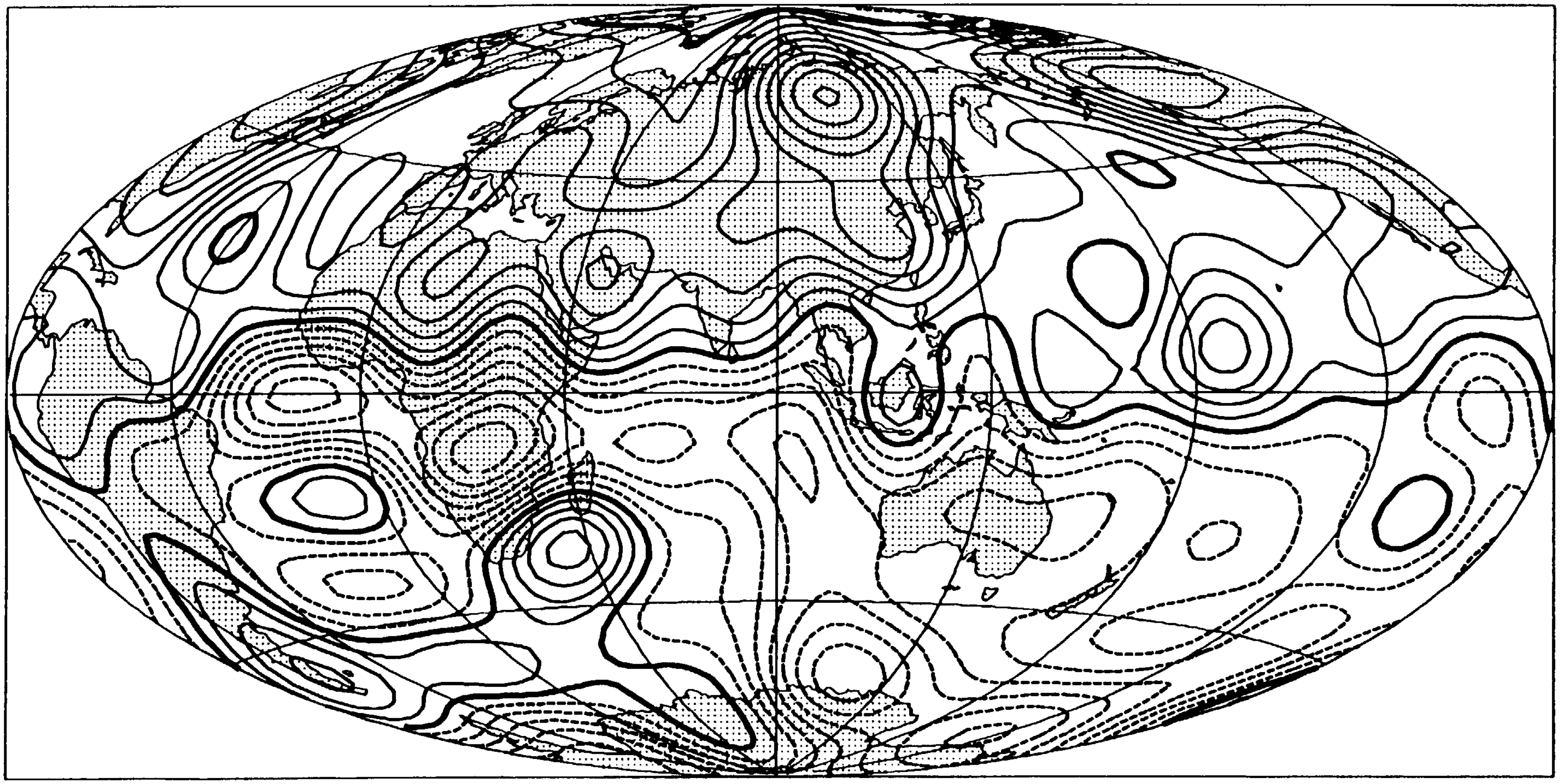

Figure 1 (a)

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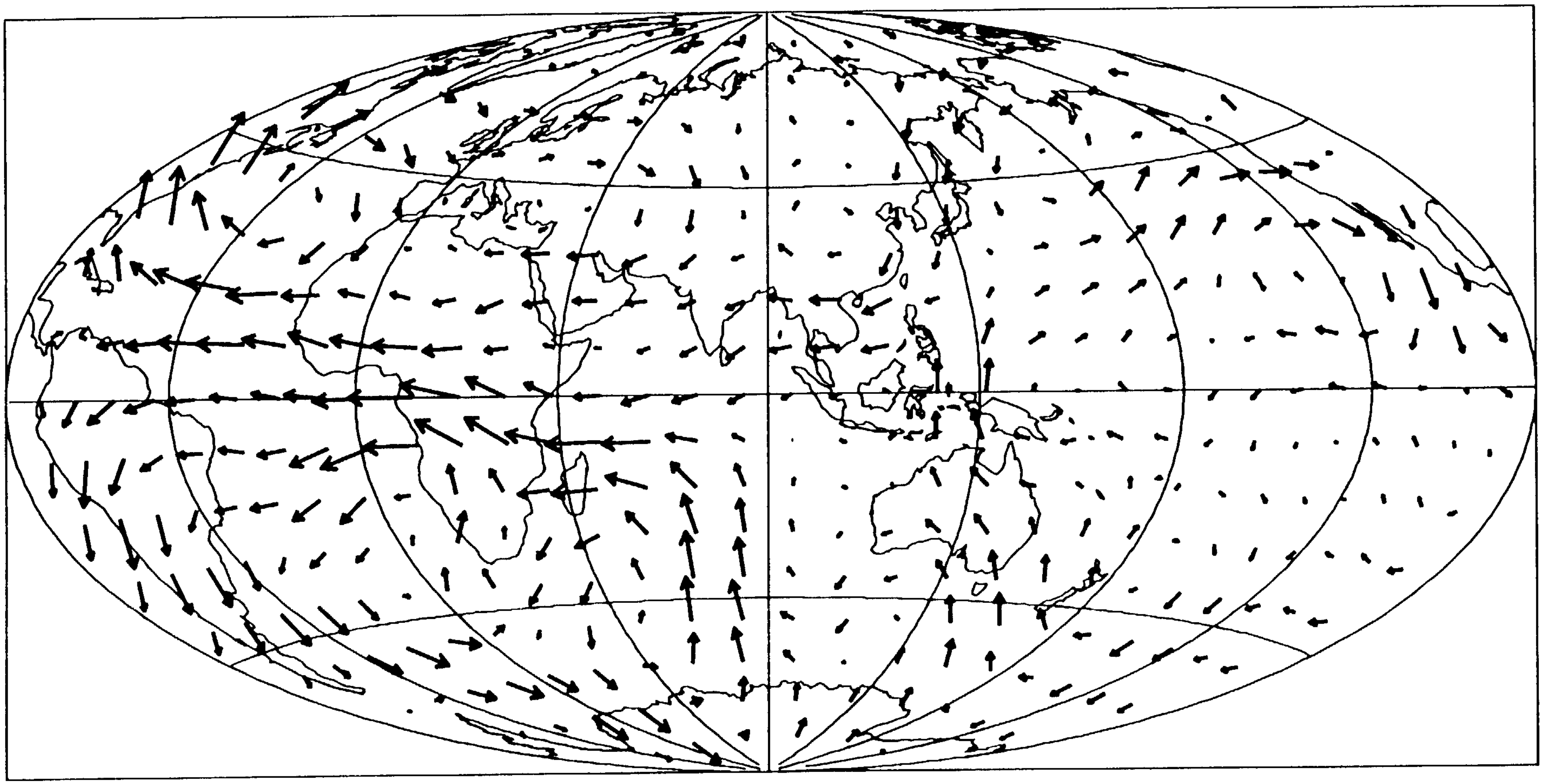

Figure 1 (b)

→ 20km/yr

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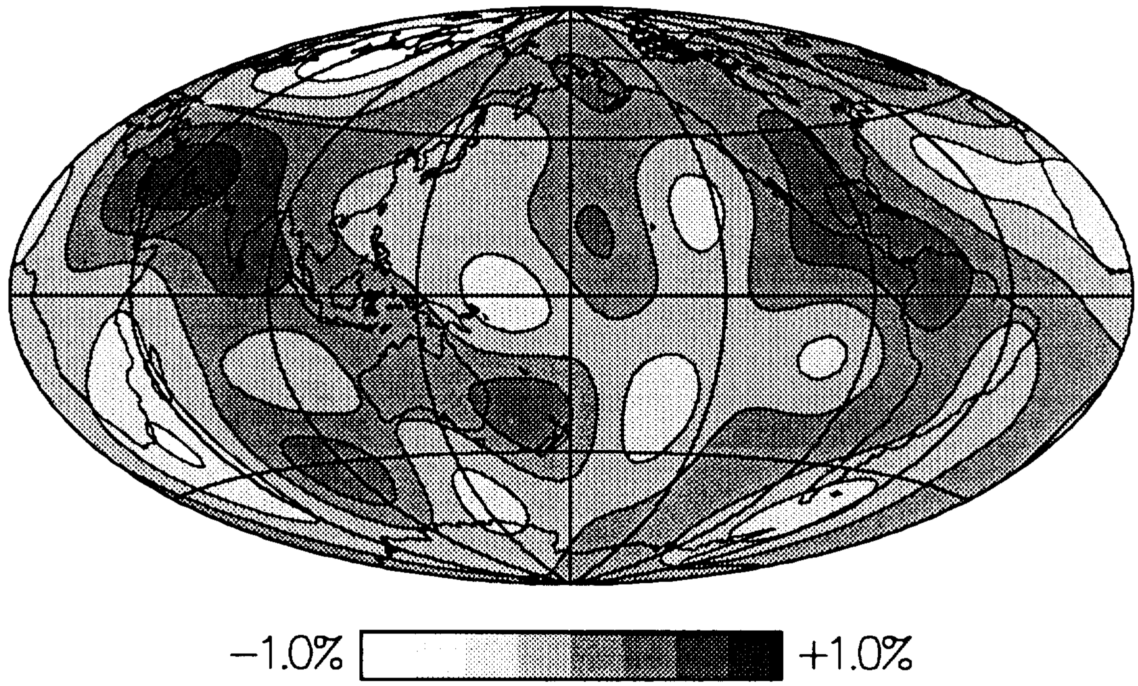

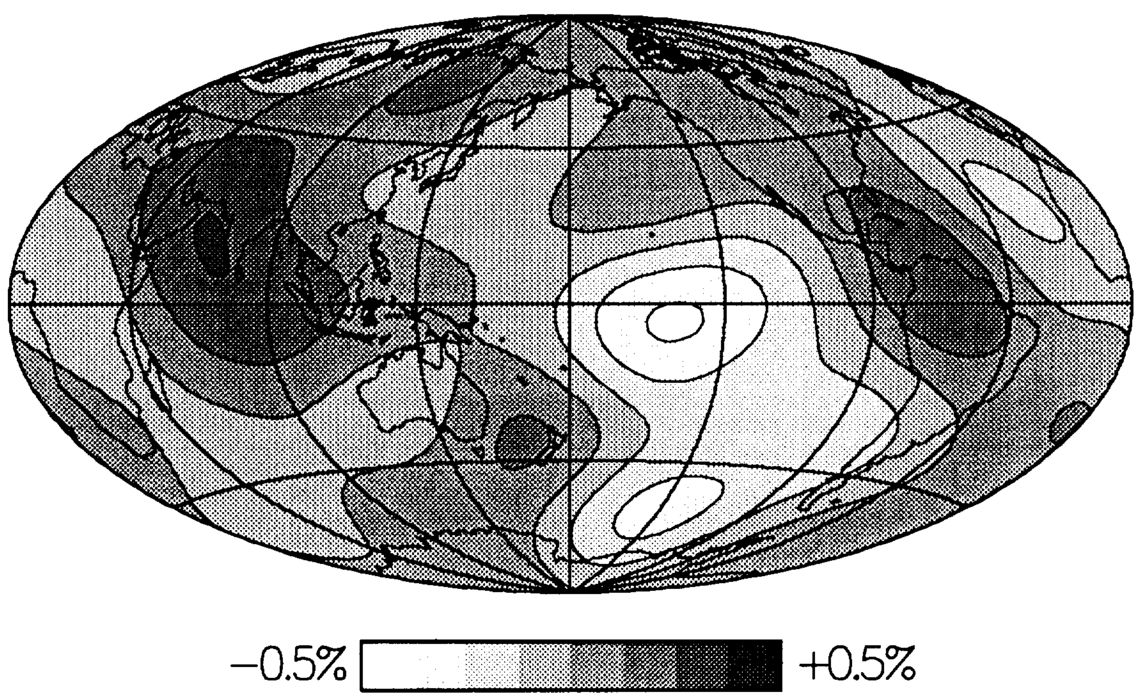

Figure 2