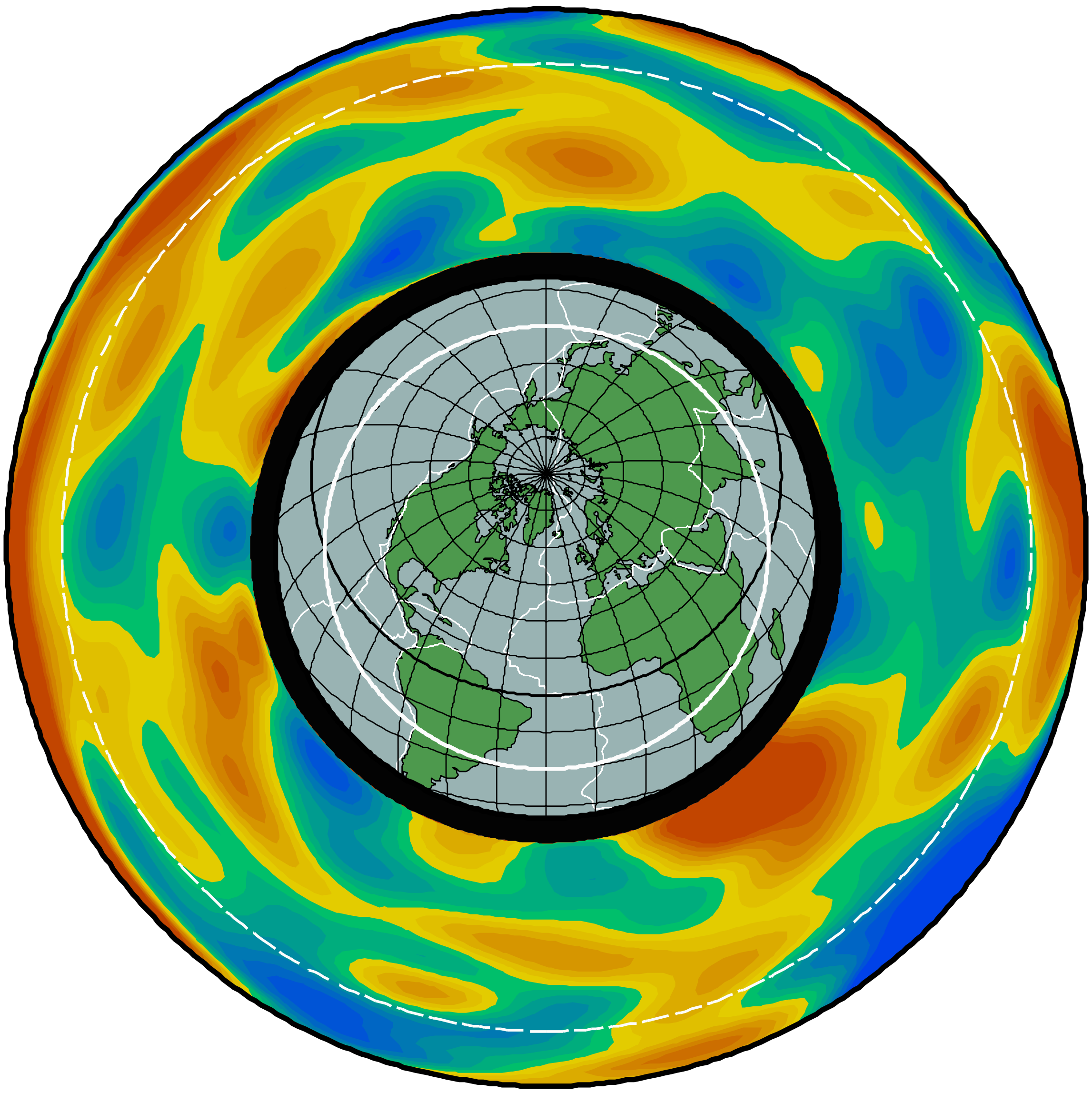
# CSEDI SCIENCE PLAN

## A Science Plan
## for
## Cooperative Studies of the Earth's Deep Interior



Prepared by the
US SEDI Coordinating Committee
May 1993

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(CSEDI)

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# 1 Summary

This is a plan outlining a new initiative in Earth Sciences, focusing on studies of the Earth's deep interior. The objective of the initiative is to make major advances in our understanding of the state and dynamics of the Earth's deep mantle and core, their influence on the evolution of the Earth as a whole and on processes that affect the Earth's surface. This is to be achieved by encouraging and facilitating cooperative research projects that cut across traditional disciplinary and institutional boundaries. The initiative consists of two principal, complementary components: a community based scientific organization and a proposed NSF program.

## 1.1 What is CSEDI?

CSEDI (Cooperative Studies of the Earth's Deep Interior) is a community initiative that has been organized by members of the SEDI (Studies of the Earth's Deep Interior) committee of IUGG and the SEI (Studies of the Earth's Interior) committee of the AGU. This activity grew out of a realization that a number of important problems related to the Earth's deep interior need a new approach for their timely solution. The approach we propose entails multidisciplinary and multi-institutional attacks on an array of fundamental problems whose solution will pave the way for significant improvement in our understanding of the dynamics and evolution of the Earth.

### What is the goal?

The goal is to discover how the Earth works: to understand how the dynamics of the Earth's deep interior controls the structure and evolution of the Earth on planetary scales; to understand complex dynamical processes in the deep interior such as the generation of the Earth's magnetic field; to discover features in the Earth's interior and relate them to its present state and history; to understand how the Earth has functioned and evolved over geologic time; and to understand the engine in the Earth's deep interior that drives plate tectonics at the surface.

### Why now?

The time is ripe for a new approach that can take advantage of recent advances in a number of disciplines. Seismic imaging of the Earth's deep interior has given hints of the convective patterns in the mantle. Advances in high pressure research have opened up the pressure and temperature range of the deep interior for laboratory investigation. Modeling of the Earth's magnetic field has illuminated some possible relations between convection in the Earth's core and structures in the lowermost mantle, providing new insights into the geodynamo. Geodetic techniques have provided new and unexpected probes of the deep interior. Advances in computers now allow reasonable simulations of flow and convection in the mantle and core. And isotopic and chemical measurements have revealed reservoirs of material in the deep interior and surface patterns of their traces.

Most important, perhaps, is the recognition of the breadth of the important unsolved problems related to the Earth's deep interior, and of the need for a multidisciplinary approaches to their solutions. Some examples of these problems are described briefly in section 1.2 and in more detail in section 4.

**What is needed?**

The vital elements of the CSEDI program are a new structure to encourage and coordinate multidisciplinary and inter–institutional research projects, and a mechanism to support them. The new structure is a coordinating committee, whose form and activities are described in sections 1.4 and 5.2. The mechanism of support is a set of goal–oriented funding programs within NSF and other governmental agencies. The nature of the proposed NSF CSEDI program is outlined in sections 1.3 and 5.1.

## 1.2 Scientific Goals: Some Examples

There are a number of scientific problems that need the approach proposed above. These are problems that by their nature require a multidisciplinary or inter–institutional effort among different groups, or that require a larger and more sustained effort than a single principal investigator can muster. Some examples will illuminate these problems.

**Subduction** This is an example of a problem on which many people work, but on which progress has been stalled by the absence of larger, coordinated multidisciplinary efforts. Subduction of cold material is a major feature of the convection that drives plate motions and the evolution of the mantle, yet our limited knowledge of it represents a basic ignorance about the dominant dynamic process in the Earth.

The problem is extremely multidisciplinary. Interpretation of deep seismicity that indicates the presence of slabs involves seismologists, mineral physicists, geodynamicists and geochemists. The cause of deep earthquakes, as well as that of their cessation at 670 km depth, is still unknown. They may be associated with mineralogical phase changes or dehydration reactions, which complicates their interpretation in terms of the stress state of the slab. Seismic tomographic results have provided intriguing, but not conclusive, evidence of structures that indicate penetration deeper than 670 km in some places, but not in others. Geoid lows correlate with deep seismic structures that may result from ancient subduction.

That no clear picture has emerged illustrates that the problem requires a broader approach than a researcher can individually muster. Results obtained by different investigators and techniques must be compared, the differences identified and clarified, and further investigations planned to resolve the problems. This will involve seismologists, geodynamicists, mineral physicists, petrologists and geochemists. The purpose of the present plan is to create a structure to bring together different disciplines for a coordinated attack on such problems.

**The core–mantle boundary and plumes** The core–mantle boundary is rich in thermal, mechanical, chemical and electromagnetic interactions. Molten iron in the core probably reacts with the silicate mantle to affect both regions, and both thermal and chemical effects influence the dynamics, such as the generation of mantle plumes. Flow in the mantle perturbs the shape of the boundary, influencing flow and the magnetic field in the core, which in turn change the Earth's rotation. Interactions occur at geological as well as daily time scales

The idea that plumes from the core–mantle boundary ascend to the surface to cause hot–spots and flood basalts illustrates the multidisciplinary nature of deep–earth problems: important effects include the thermal and chemical state and the shape of the core–mantle boundary, the density, rheology and flow pattern of the mantle, melting and chemical interaction with the mantle and lithosphere, and mechanical effects such as the initiation of continental rifting. Plumes may provide the only direct evidence of the material in the deepest mantle.

All of these processes have been discussed in various works, yet it is clear that integrating the different approaches needed to deal with the problem requires the active and sustained collaboration of a number of scientists from different disciplines.

**The geodynamo problem** One of the most intriguing, and longest standing, problems in our understanding of the Earth's deep interior is the origin and evolution of the Earth's magnetic field. Although a dynamo process is now widely believed to operate in the outer core, the details — in fact, even the most basic elements — of this process are not well understood.

Developments in a number of fields suggest that substantial progress could be made on this problem. Magnetic field observations, especially from satellites, have provided new views of the magnetic field at the core-mantle boundary. The pattern of convection at the core surface is being mapped. Seismology has provided new images of the structure of the mantle immediately above the core. High-pressure experiments have begun to constrain the properties of the core. Geodetic observations have revealed the coupling between the core and mantle, a vital ingredient of the dynamo problem.

These new results place constraints on the dynamo problem, and provide much needed boundary conditions, but they must be coupled with numerical studies of the dynamo, possible with the new generation of high-speed supercomputers. This will require that investigators from different disciplines come together to address this problem.

**Other problems** There are a variety of similar problems that require variations of the approach that we are calling for; these include:

— Seismic Earth models provide a view of the Earth's interior that is the basis for most other studies. Developing modern models requires the assembling and analysis of a large amount of data, together with choices of inversion techniques and trade–offs. A coordinated effort is needed to to develop and reconcile seismic models based on different types of data, as well as to propose and develop means or experiments for investigating reasons for discrepancies. The work would involve collaboration between groups working with different data types or inversion techniques, as well as those who can examine the dynamical consequences of particular models, such as on the geoid or core–mantle boundary topography.

— Mantle convection and flow models provide the basis for studies of dynamical effects ranging from plate motions to the distortion of the core–mantle boundary. It is currently not feasible to construct a global model with sufficient resolution to resolve all of the phenomena of interest, and a number of different models are needed for purposes ranging from global flow models that can be used to trace the transport of material throughout the mantle, to more detailed models of local instabilities and the development of plumes. The development of such models requires the involvement of geodynamicists, mineral physicists, petrologists as well as numerical analysts. Also it is essential that convection and flow models be well tested, readily usable, and available to a range of workers. Involvement of users in the development of numerical models will help make sure that they are indeed useful.

— The volatile flux from the solid Earth into the atmosphere, such as the present observed flux of $^3$He and $^{20}$Ne, suggests that either a reservoir (presumably primordial) remains in the Earth or that these volatiles have been reintroduced into the Earth by subduction. The apparent depletion of Xe in the Earth relative to other noble gases also may be related to this question. Theoretical and experimental studies of the degassing and regassing of the Earth are required to understand the magnitude and mobilities of volatile reservoirs in the Earth's deep interior and relate them to the evolution of the atmosphere and hydrosphere. This problem draws on knowledge of the internal structure of the mantle from seismology, mantle convection and flow, and geochemistry and the properties of minerals deep in the Earth.

— Hot–spots and plumes, and their role in surface tectonics and episodic volcanism.

— Geochemical reservoirs in the mantle, and the sources of magmas and volatiles (especially greenhouse gases) that effect their abundance in the atmosphere and ocean and global climate.

— Relations between plate motions and mantle flow, and the extent to which deeper convection controls surface tectonics.

— Role of mantle dynamics in continent assembly and breakup, and in changes in topography, sea level and sedimentation–erosion regimes.

— Interaction between dynamics and the thermodynamics in the transition zone, and the depth scale of mantle convection.

Most of these require the development of seismic and flow models, and all require a multidisciplinary, multi–institutional approach for rapid progress to be made.

## 1.3 The NSF CSEDI Program

The primary function of the NSF CSEDI program will be to provide support for cooperative multidisciplinary studies, so that accelerated progress can be made on fundamental problems of the Earth's deep interior. The program is intended to support research that is presently very difficult or impossible to support under the existing grants program and is not appropriate for a Science and Technology Center, but which is crucial for advances in understanding the Earth's interior. New funds will be required. These funds will be distributed by NSF using the usual mechanisms of peer review and panel evaluation of proposals. The level of support provided by the program needs to be substantial enough that the commitment to the research projects is more than nominal.

### 1.3.1 Program focus

The program will be open to all investigators who wish to submit proposals, and proposal ranking will take into consideration several criteria related to the multidisciplinary, multi- institutional aspects of the CSEDI initiative. These include:

- Proposals should demonstrate the possibility of making accelerated progress on major problems of global significance.
- The proposed work should draw from, contribute to, or be aimed at establishing more than a narrow disciplinary perspective.
- The investigators should come from more than one research unit.

### 1.3.2 Scope of the program

The program would support at any one time 4 or 5 research projects (see section 4.2 for examples) each with a fixed duration and perhaps three infrastructure projects (see section 4.3 for examples). Each project would be administered by those actively involved in it. Using a rough figure of $400K/yr for each project results in an annual budget of roughly $4M for the NSF program.

## 1.4 The Coordinating Committee

The coordinating committee is the administrative manifestation of the CSEDI initiative within the scientific community, and has the broad charge of encouraging and coordinating multidisciplinary and inter- institutional research focusing on the Earth's deep interior. The members of the committee will be regularly chosen by the community to serve fixed terms. The specific charges to the committee include:

- organizing or coordinating topical symposia and other activities related to the CSEDI initiative;
- promoting consensus within the US SEDI community on important problems of highest priority for focussed effort, and assisting in the resolution of controversies;
- communicating this consensus to the larger community and governmental agencies;
- disseminating discoveries and other results of the program as part of an educational outreach program.

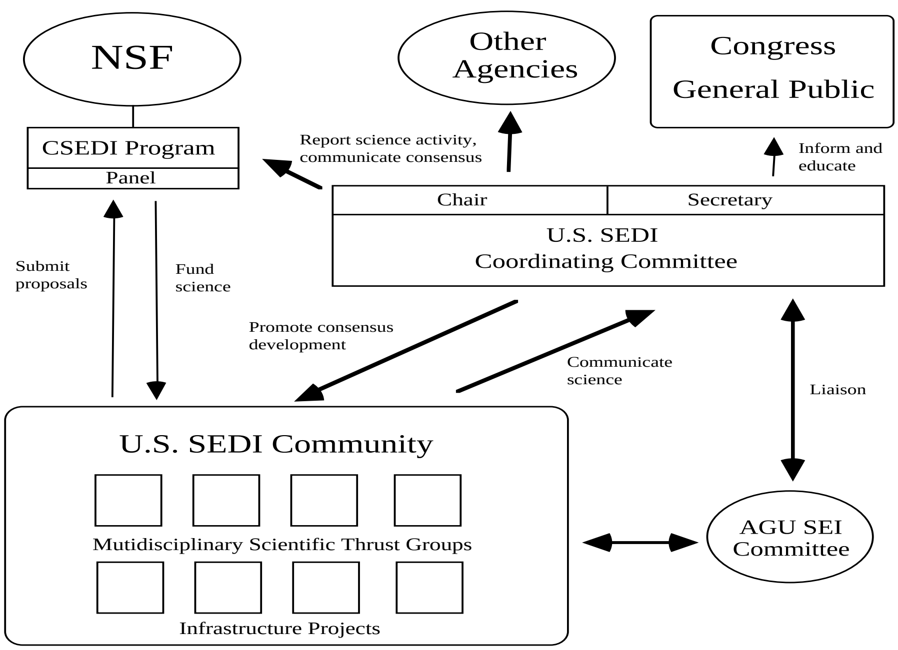



Figure 1.4.0-1: An illustration of the various components of a NSF CSEDI program, and their interactions.

# 2 Introduction

A quarter of a century ago the earth sciences experienced a revolution with the realization that the surface of our planet is divided into a number of rigid plates which are in constant inexorable motion. We now view the Earth as a dynamic planet, driven by deep-seated forces that cause earthquakes and volcanos, build mountains and gradually reshape the entire surface of our planet. However, this has been an incomplete revolution, as the origin and nature of the driving force behind the plate motions remain obscure. But, owing to recent advances in our ability to remotely sense and model the Earth's deep interior, we now are in a position to identify and quantify these forces, thus completing the revolution. However, realization of this goal will require an unprecedented level of cooperation among the various branches of geoscience relevant to the deep earth. This document is a call for a program of Cooperative Studies of the Earth's Deep Interior (CSEDI), which will serve to facilitate and coordinate this activity.

The fundamental goal of CSEDI is an understanding of the origin, evolution, structure and dynamics of the deep-Earth system. The deep-Earth system consists principally of the lower mantle, the core and the core-mantle boundary region, and encompasses the interaction of the deep and shallow mantle through processes of mantle convection including, in particular, plate subduction and mantle plumes.

Within the past few years there have been a number of significant advances in our ability to analyze and simulate the deeper regions of the Earth. For example, we have begun to image the three-dimensional structure of the mantle and core using seismic, gravity, geoid and topographic data, and to map the magnetic field and velocity structure at the top of the core using geomagnetic data. Furthermore, we can now produce and sustain in the laboratory conditions existing in the deep interior. Concurrently, computing speed has developed to the point where we can begin to model the three-dimensional, time-dependent flows and structures believed to occur within the mantle and core. Equally important have been the advances in our ideas of internal structures and processes, such as plumes in the mantle and compositional convection in the core. Each of these advances represents a crucial element necessary to build a consistent picture of the dynamic interior of our planet. What is missing is the catalyst necessary to bring these disparate elements together. The program proposed here should serve as this catalyst.

The problems addressed are of considerable intellectual interest, and have significance for a variety of areas of Earth science. Most processes on the Earth are driven or influenced ultimately by the heat engine in the interior. Understanding the processes in the deep interior is as challenging as unravelling how stars work. The geologic record provides a long history of the evolution of the Earth, and the challenge is to discover how this is related to the deeper processes. Recent discoveries have indicated that such deep seated processes may have important consequences. Plumes from deep in the mantle are believed to cause massive outpourings of flood basalts on the surface. These have been related to drastic changes in atmospheric composition, and to possible extinction events. The motion of continents over changing convection patterns in the mantle causes changes of relative sea level, and accounts for the successions of sea level changes that have led to the complexities in the stratigraphic record. In short, the key to many problems of this sort is understanding how the Earth's interior works.

The new initiative will foster and coordinate multidisciplinary and/or multi–institutional collaborations addressing fundamental problems in the Earth's deep interior. The types of research activities to be fostered by CSEDI fall broadly into two categories: research thrusts and scientific infrastructure. Research thrusts are focused activities in areas which are ripe for rapid advancement or resolution of long-standing controversies, such as depth of penetration of slabs into the mantle and the temperatures within the core. Scientific infrastructure consists of the development and verification of large-scale numerical codes, similar to the general circulation models which have been developed in the atmospheric sciences, and the development of Earth models based on seismic observations and other considerations.

The activities fostered by CSEDI will be carried out by scientists in the community who cooperatively organize and submit proposals to attack problems on which rapid progress may be made by a coordinated effort. The opportunity to propose will be available to all scientists, and proposals will be subject to the usual peer review. Some activities of CSEDI will be coordinated by a committee having diverse disciplinary and institutional representation; this committee will help organize topical symposia on important problems, serve as a liaison between the community, NSF and other agencies, and promote and communicate the consensus of the community.

The following sections spell out in more detail the scientific motivation for the proposal, some examples of problems on which rapid progress could be made under the program, and the proposed organization and operation of the proposed program.

# 3 Scientific Motivation for the CSEDI Initiative

One of the great achievements of this century has been the development and application of methods to determine deep structure and processes inside the Earth based on surface observations. The resulting understanding of the inaccessible depths of the planet, as overviewed in this Chapter, is a scientific feat fully on a par with the remarkable advances in astrophysical spectroscopy which have revealed the composition and relative motions of distant stars. However, our knowledge of Earth's deep interior is still very limited, and a concerted effort is required to better understand the dynamic system on which we live.

## 3.1 NATURE AND CHARACTER OF DEEP-EARTH STUDIES

By their very nature, studies of the Earth's deep interior all intrinsically involve remote sensing procedures. Observations of various geophysical phenomena such as the seismic, gravitational, geomagnetic, and geoelectric fields, as well as geochemical analysis of the few rock samples erupted from the upper mantle, provide most of our direct knowledge of the deep Earth system. An extensive body of geophysical inverse theory has evolved to extract information from the surface observations and to develop models for the interior [Figure 3.1.0-1]. For several decades the various deep Earth disciplines have evolved separately, with relatively little overlap in either data collection or model construction, and a high level of sophistication in each field has been achieved. For example, a first-generation of global three-dimensional models for the elastic velocity heterogeneity throughout the planet has been developed by seismologists; numerical models of mantle wide temperature-dependent viscous flow with realistic material properties have been developed by geodynamicists; and models of the magnetohydrodynamic flow in the outer core responsible for the secular variation of the magnetic field have been presented by dynamo theorists. It is increasingly recognized that future progress in understanding Earth's interior will be achieved by bringing together the various disciplines, simultaneously interpreting the geophysical and geochemical observations and developing unified models for the internal processes. The CSEDI initiative will abet the collaborative efforts needed to make new discoveries and major advances in our understanding of the deep interior.

### 3.1.1 Remote observations: Seismic, Magnetic, Gravitational, and Geochemical

The most detailed information about the Earth's interior comes from the field of seismology. This discipline involves analysis of seismic waves, usually excited by earthquake faulting or underground explosions, that propagate throughout the planet and are recorded at the surface by seismometers. These elastic waves are governed by well-understood physics and propagate with spatially-localized characteristics that enable high resolution models of deep Earth internal material properties to be extracted from global recordings of natural and human-induced vibrations. Waves spread spherically outward from any given source, and produce a complex, yet well-ordered total wavefield as a result of interactions with the layered structure of the planet [Figure 3.1.1-1]. This 'fingerprint' is used to study the deep structure.

Global recordings of seismic waves provide the data seismologists need to study the deep interior. Major national and international seismic instrumentation initiatives have been ongoing for about 10 years to globally deploy a new generation of very broadband high dynamic range digital seismic recording systems which will provide improved resolution of the deep interior. Analysis of the

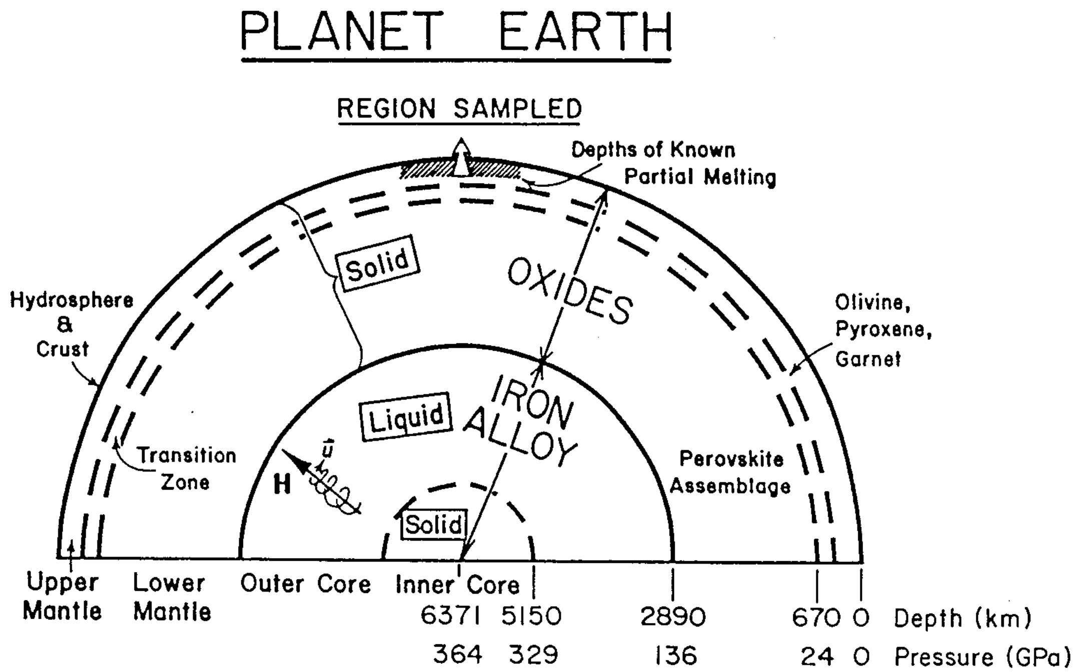



Figure 3.1.0-1: A schematic of the layered structure of the Earth, deduced from many geophysical and geochemical studies this century. The planet is stratified, with chemically distinct core, mantle and crustal layers, and there are mineralogical phase transitions in the upper mantle transition zone as well. All depths in the planet are in dynamic motion, with rapid convection in the outer core producing the magnetic field, while sluggish motions in the mantle drive plate tectonic processes at the surface.

existing tens of thousands of digital earthquake recordings and millions of accumulated seismic phase travel times has progressed profoundly due to both theoretical and computational advances. Seismic waves have revealed the basic layering of the planet [Figure 3.1.1-2], including chemical and phase boundaries at various depths [Figure 3.1.1-3], as well as the gradual variations of properties due to increasing confining pressure. The spherically symmetric, average seismic velocity and density structures everywhere inside the planet are known to within a percent or two with high confidence, and recent efforts are beginning to map out the aspherical structure as well (see sections 3.2.1).

Equally impressive are the recently developed models of fluid motions in the outer core, more than 2900 km below us [Figure 3.1.1-4. These models are derived from surface and space-based observations of the Earth's magnetic field. Motions of the molten metallic alloy in the outer core produce magnetic fields, components of which can be observed and studied at the surface. The convective regime within the core is believed to be very complex, but it has symmetries which result in a predominantly dipolar magnetic field aligned close to the rotational axis of the Earth. Rapid variations are observed in the surface magnetic field, as well as intermittent reversals of the polarity of the main field. Rocks cooling through their Curie temperatures or precipitating in the presence of the magnetic field acquire and preserve the local magnetic direction, providing a geological history of the field extending back hundreds of millions of years.

Developing a theory for the excitation and variability of the magnetic field has challenged geophysi-

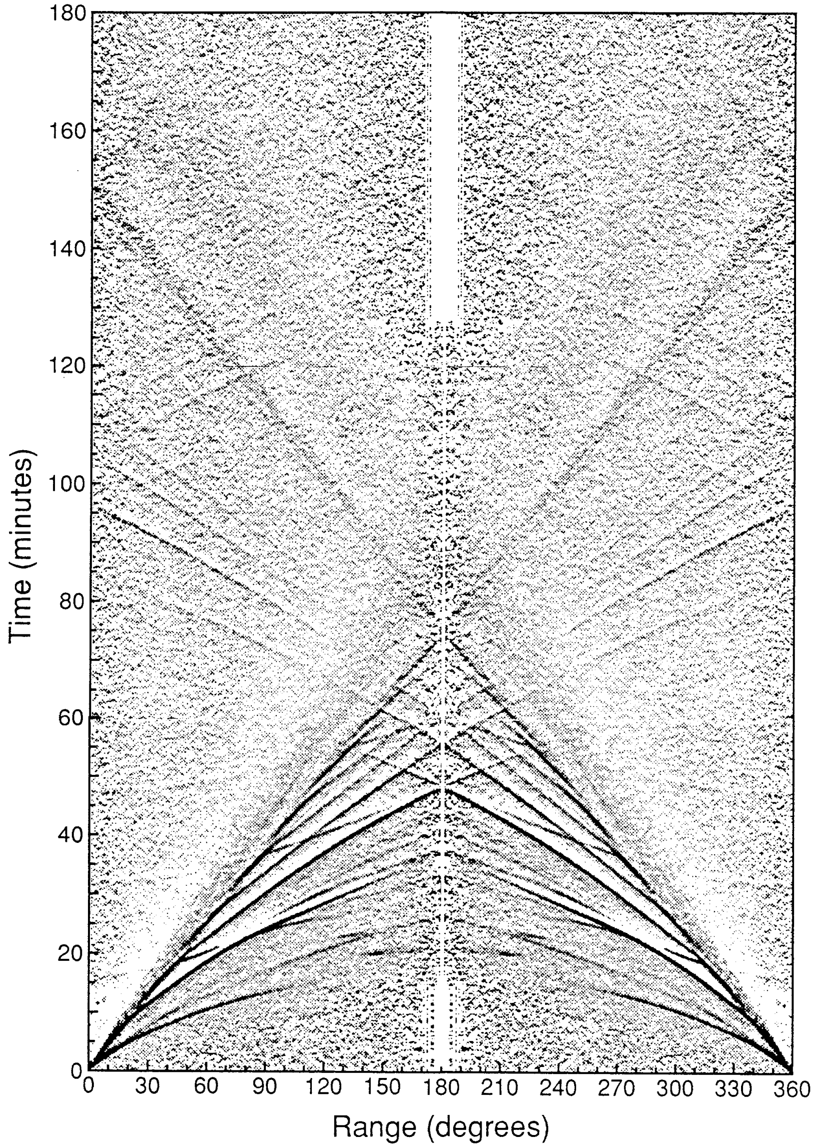



Figure 3.1.1-1: A stacked record section of the transverse (SH) component of long- period Global Digital Seismic Network seismograms, plotted as a function of distance from the respective sources. The symmetry is caused by the spherical structure of the Earth, and the distinct branches that appear in the total SH wavefield represent the multiple S wave interactions with the free surface and the internal layering of the mantle. From data such as these seismologists have developed models of the one- dimensional structure of the planet.

cists for centuries. Improvements in magnetic observatory instrumentation and global mapping by satellite magnetometers have greatly improved the magnetic data base over the past few decades. This has been paralleled by development of theory and inversion programs for performing the massive calculations involved in solving the magnetohydrodynamic equations. While we are still far from a complete understanding of the geodynamo, there is now substantial consistency in models

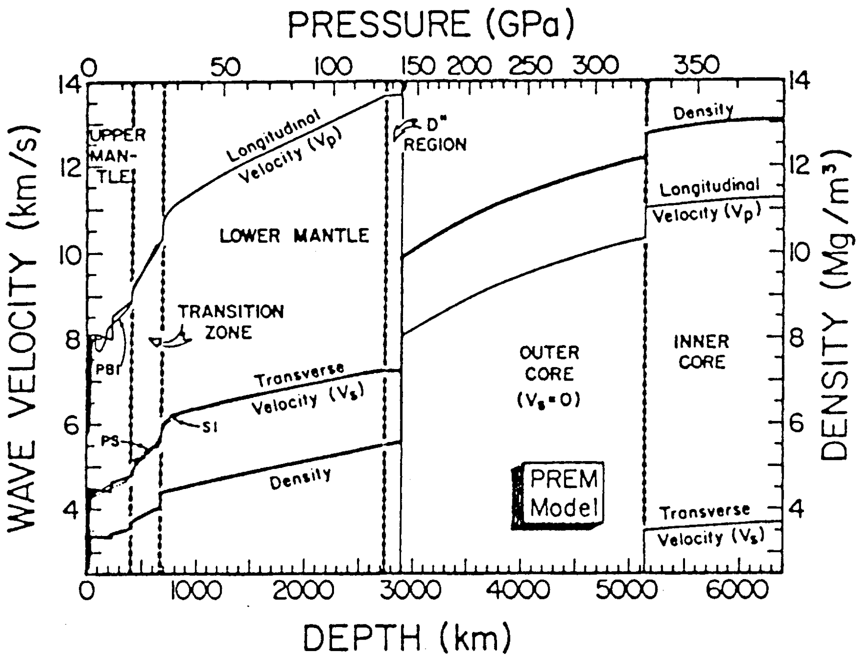



Figure 3.1.1-2: The Preliminary Reference Earth Model of P velocity, S velocity, and density as a function of depth in the Earth.

of the outermost core flow obtained by inversion of the magnetic field secular variations over time scales from years to centuries [Figure 3.1.1-4]. For this problem the underlying physics are far more complex than for seismic waves, and the corresponding non-uniqueness is greater, but steady progress has been made in finding flow models consistent with the surface observations for a variety of reasonable boundary conditions. It is now believed that better constraints on the correct boundary conditions may come from the seismological models for deep mantle structure, since these provide information about the variable heat flux out of the core.

The shape of the surface of the Earth and the slight irregularities in its rotation also reveal dynamic motions and density heterogeneities deep inside the planet. The material properties of the Earth allow viscous deformation under the presence of long- term stresses, resulting in solid-state convection and driving surface plate motions. The internal flow produces dynamic stresses that distort internal boundaries as well as the surface of the Earth. Since the source of most internal stresses in the interior is thermally and chemically induced density heterogeneity, the gravitational field and surface topography are among the most direct indicators of deep internal dynamics. Departures from hydrostatic symmetry also influence the rotation of the planet, and exchange of angular momentum between the core and the mantle causes multi-year scale variations in the rotation rate. Observations of the rotation irregularities constrains the physics of core-mantle coupling caused by topography on the core- mantle boundary and electromagnetic coupling across the boundary.

Satellite-based information has again played a critical role in improving the data base on the detailed figure of the Earth and its erratic spin. Vast increases in computational power have enabled analysis of the satellite data. Analysis of the gravitational field and the equipotential geoid have revealed very long wavelength undulations that cannot reasonably be attributed to any shallow structure.

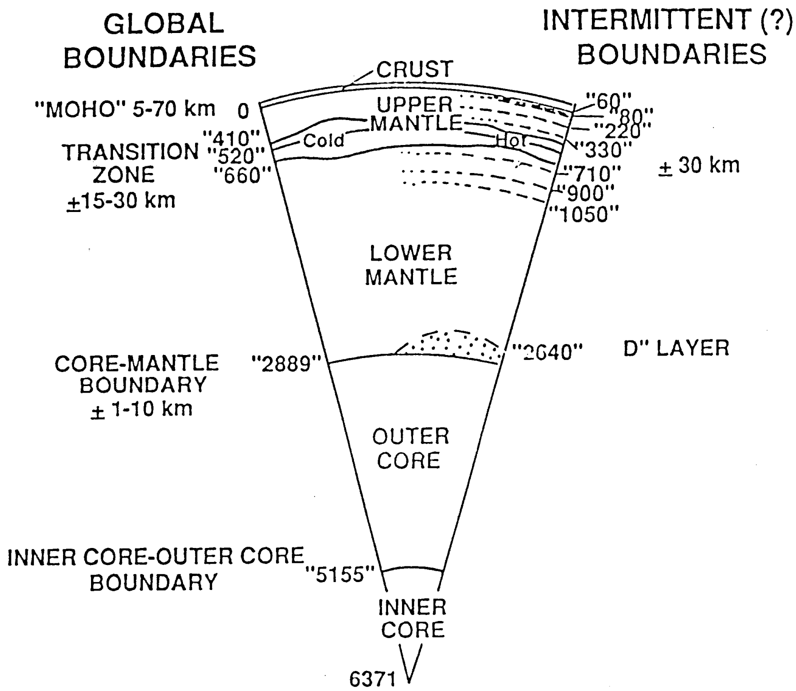



Figure 3.1.1-3: Schematic cross–section through the Earth identifying major boundaries in the planet that are observed globally (left) and intermittently (right). Estimates for the variation in the depth of each are given where available. The 410– and 660–km boundaries seem to be deflected in the opposite sense by temperature variations in the transition zone, with peak-to-peak variations as large as 60 km possible.

Since the gravitational field lacks the localization properties of seismic waves, interpretation of the causal deep Earth structure cannot be done uniquely, but the 1980's brought about the first joint interpretations of deep seismic models and very long wavelength geoid features [Figure 3.1.1-5], with breakthrough interpretations in terms of deep mantle flow. This advance is just a harbinger of future discoveries to come as an increasingly interdisciplinary approach is taken to understanding the deep interior.

While there are well-developed procedures for interpreting the various types of geophysical information, it is much more challenging to provide chemical and thermal interpretations of the resulting models. Our basic concepts about the bulk composition of the interior are primarily derived from cosmochemical models and from chemical analysis of rocks at the Earth's surface. The relative abundance of elements in meteorites and in the Sun provide analogs for the bulk composition of the planet, but clearly Earth is unique in its particular degree of differentiation and its minor element constituents, so this line of reasoning requires further constraints. The isotopic heterogeneity of rock samples derived from mantle magmas provides direct constraints on the chemical heterogeneity within the upper portions of the mantle. The latest generation of mass spectrometers can analyze the detailed chemistry and isotopic distribution of minor elements in these rock to

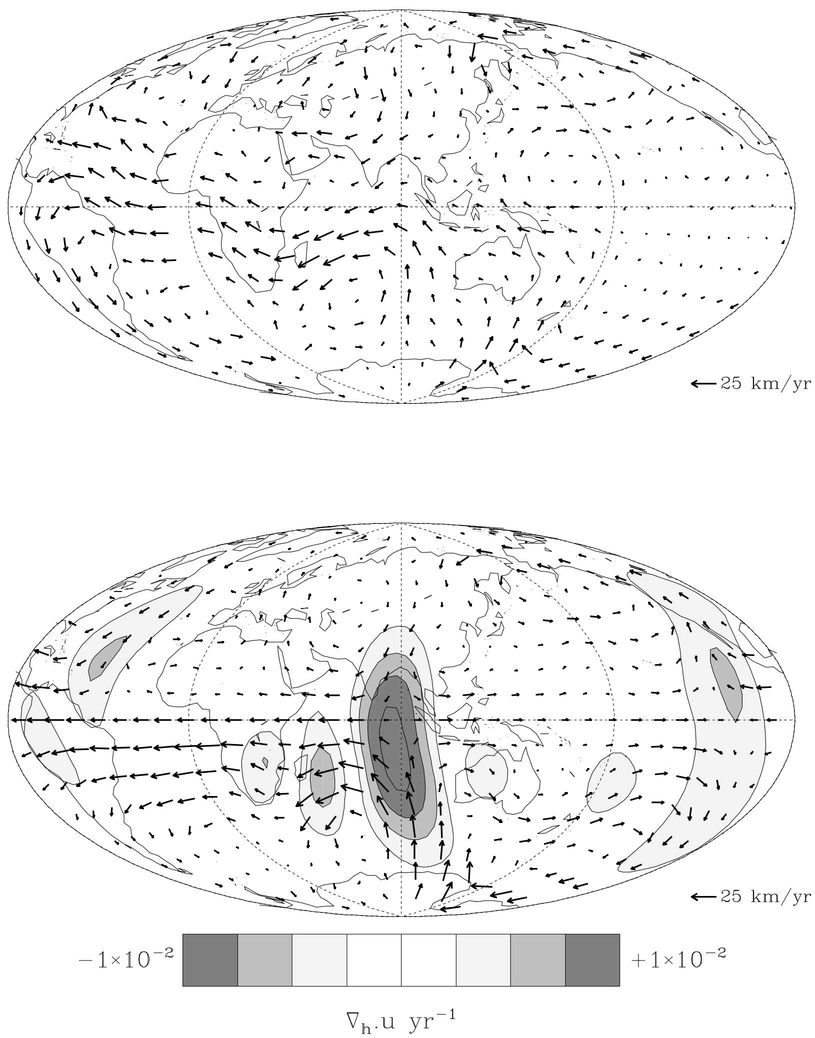



Figure 3.1.1-4: Flow fields at the top of the core calculated on the basis of models of the magnetic field at the core–mantle boundary. The top figure assumes that the flow is toroidal; the lower assumes geostrophic flow.

characterize their origins.

Our primary information on the timing of geological processes comes from isotope geochemistry. Indeed, geochemical studies offer at least two kinds of information complementing the geophysical observations of the interior. First, through the identification of characteristic signatures in their compositions (e.g., the distribution of rare-earth, noble-gas, or other trace elements or isotopes), the genetic relationship between broad classes of rocks can be recognized. In this way, continental crustal rocks can be related back to the mantle source from which they differentiated, for example. Several "geochemical reservoirs", geochemically distinct source or product regions, have been identified. Once defined, the techniques of isotope geochemistry allow us to date the reservoirs; that

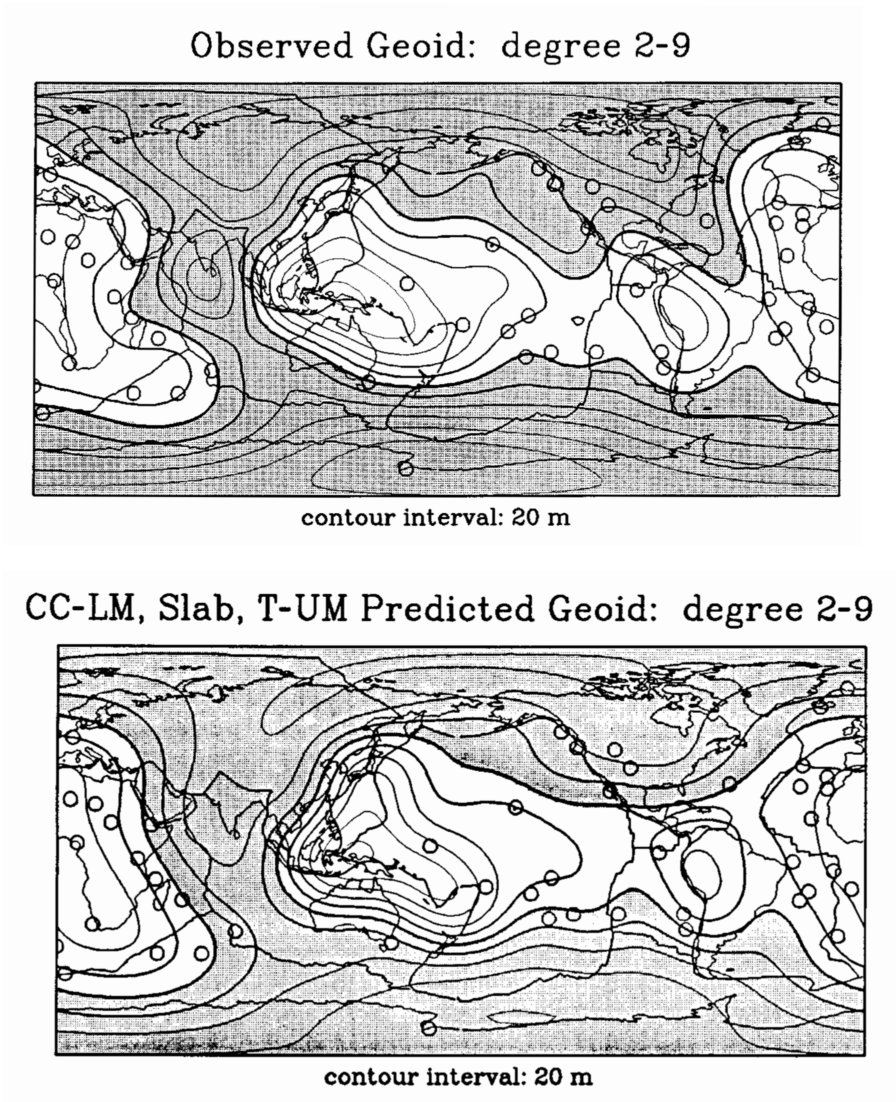



Figure 3.1.1-5: Comparison of the observed long-wavelength geoid referred to the hydrostatic figure (top) and a calculated geoid which includes contributions from lower and upper mantle tomographic models for degrees 2-4 and from slabs for degrees 2-9 (bottom).

is, to determine when they became distinct and how long they have remained separate. This second type of information, temporal resolution of past global- scale geological processes, is uniquely provided by geochemistry. A notable example of this is the demonstration that the bulk of the continental crust was differentiated, extracted from the mantle reservoir, within the first third of Earth history. However, the geochemical tracers alone do not reveal the dynamic configuration that has given rise to the inferred heterogeneity [Figure /reffig:4models], and integration with seismic and geodynamic models is an emerging focus.

Mantle xenoliths from kimberlite pipes provide us with samples from the upper mantle. Most of these mantle fragments originate at depths shallower than 200 km, but recently, samples have been identified that may originate as deep as 400 km. Even so, direct sampling of the mantle is

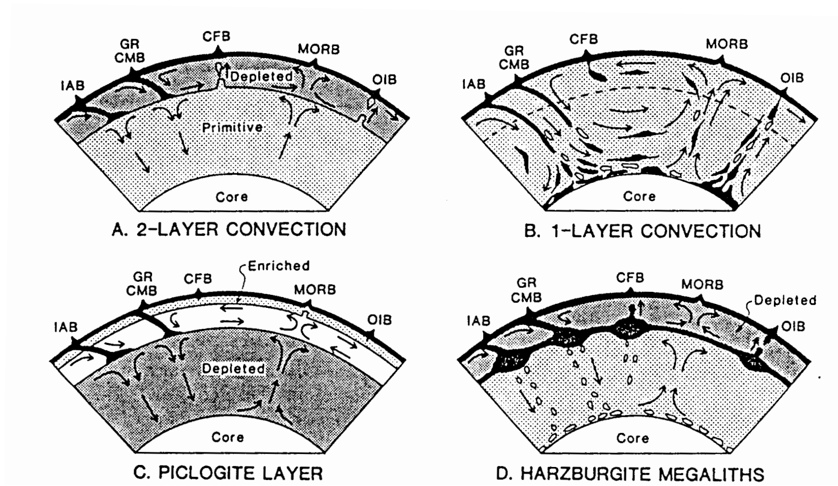



Figure 3.1.1-6: Four contrasting models for mantle convection proposed mainly on the basis of geochemistry.

extremely sparse and, at best, reaches to depths of only 13% of the depth to the core. Consequently, the composition and petrology of most of the mantle must be inferred from geophysical techniques. Important constraints also come from reconciling cosmochemical models for the bulk composition of the Earth with *in situ* material properties measured in the laboratory.

### 3.1.2 Experimental studies of the deep Earth environment

Simultaneous with the development of geophysical and geochemical 'probes' of the Earth, there have been great advances in our ability to experimentally reproduce the range of temperature and pressure conditions existing within the Earth in controlled mineralogical experiments. Experimental work, using shock wave apparatuses, diamond-anvil cells, and large anvil pressure devices [Figure 3.1.2-1] is critical to interpreting the seismological models of internal elastic and anelastic properties. Experimental techniques using the latest technology in laser heating systems, various spectroscopic analysis procedures, and high resolution x-ray diffraction using synchrotron radiation have propelled the field forward. There has been more than a 50-fold increase in the combined pressure-temperature conditions that can be achieved experimentally in the past 15 years.[Figure 3.1.2-2]

Given a broad, multidisciplinary foundation of observations, it is possible to draw strong conclusions about the basic composition and state of deep regions of the interior. It is now widely accepted that the outer core is molten iron alloy, with about 10% of a light component such as oxygen, sulfur or silicon, and that the predominant mineral in the lower mantle is $MgSiO_3$ in the octahedral perovskite structure [Figures 3.1.1-3, 3.1.2-3]. The high degree of confidence assigned to such interpretations of regions that we have never directly sampled stems from the consistency of cosmochemical, seismological, mineral physics, geodynamical and geomagnetic observations.

An important aspect of progress in deep Earth research has been the testing of hypotheses generated by one discipline or another. For example, the mineralogical phase transformations that occur in

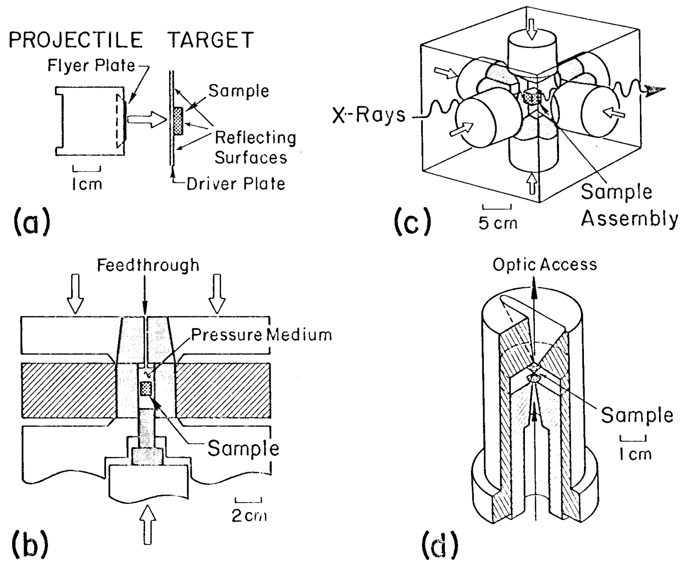



Figure 3.1.2-1: Schematic illustrations of three ultra-high pressure techniques: dynamic (a), large-volume static (b, c), and diamond cell (d) (open arrow indicate force or impact). (a) Shock-wave (Hugoniot) measurements consist of a metal plate (flyer plate) embedded within a projectile impacting a stationary target at velocities of the order of kilometers per second. The target includes a sample attached to the back of a metal plate (driver plate). (b) Piston-cylinder experiments involve compressing a pressure medium (either liquid or solid) by advancing the piston within the cylinder (shown here in cross section), there by pressurizing the sample. Typically, hard metals (e.g. WC) are used for the piston and cylinder, although sintered diamond has also been used for the end of the piston. A narrow feedthrough hole, appropriately sealed within the cylinder, allows electrical leads to be brought into the sample area from the outside. The leads are used for monitoring temperature and pressure and for bringing current to a resistance heater around the sample (not shown). (c) Cubic anvil design of large-volume press has been extensively used in Japan since the late 1970s. The sample assembly often consists of further (pressure intensifying) anvils, gasketing material, pressure media, calibration standards, and the sample. In this design, X rays and electrical leads can pass through gasketing material between the six anvils, thus traversing the entire pressure vessel and sample assembly along a diagonal. The anvils are typically made of steel, with WC or sintered diamond tips. (d) Diamond cell of the Mao-Bell ("Megabar") design consists of two gem-quality diamond crystals being pressed together in a in cutaway view). The sample is placed between the points of the two diamonds and can be directly viewed through the diamond anvils. X rays and other forms of radiation can be used to probe the sample along the same optical path. The piston and cylinder are typically made of metal (e.g., hardened steel with WC backing plates behind the diamonds) and are placed within a lever-arm assembly or an opposed-anvil press in order to apply force to the diamonds.

common mantle minerals such as olivine were anticipated by experimentalists to cause mantle discontinuities before these structures were actually well mapped out by seismologists. There has been a continuing symbiotic bootstrapping in deep Earth investigations between these disciplines.

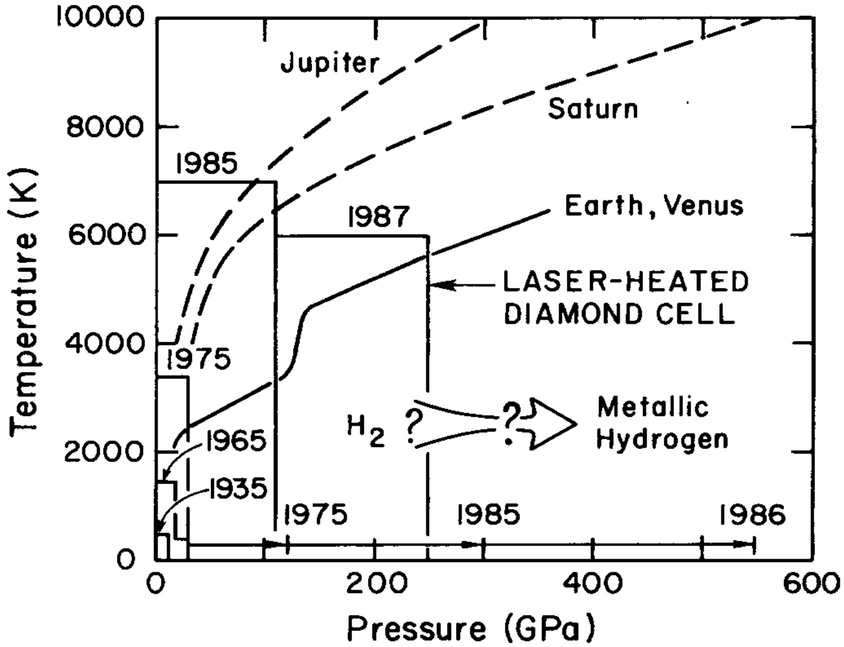



Figure 3.1.2-2: Summary of sustained pressure-temperature conditions that have been achieved in the laboratory (*arrows* at 300°K and fields with dates) compared with the pressure above which hydrogen is expected to metallize (*open arrow*). All of the advances shown after 1965 are based on the diamond cell, laser heating having been used to generate peak temperatures of ~3000–7000°K. Average temperature–pressure profiles through the entire depth range of Earth and Venus, and as modeled for the interiors of Jupiter and Saturn, are shown as *solid* and *dashed curves* (the *curves* shown here represent conditions that include over 55% and 95% of the volumes of Jupiter and Saturn, respectively)

Seismological evidence for anisotropic structure in the solid iron inner core has motivated mineral physics experiments on the intrinsic anisotropy of high pressure forms of iron that may have not been considered otherwise. Current experimental work on possible chemical reactions between the core and the lower mantle are motivating detailed seismological investigations of the core-mantle boundary in an effort to detect any possible reaction zone. Detailed petrological models of upper mantle chemistry in combination with mineral physics experiments yield predictions of seismic velocity and density structure which can be compared with actual observations [Figure 3.1.2-4]. Predicted effects of chemical, thermal and phase boundaries from mineral physics experiments have motivated detailed analyses of the sharpness and topography on mantle seismic discontinuities [Figure 3.1.2-5]. While much progress has been made and will continue to be made in this see-saw fashion of separate disciplinary advance, many outstanding major problems require a more coordinated multidisciplinary approach.

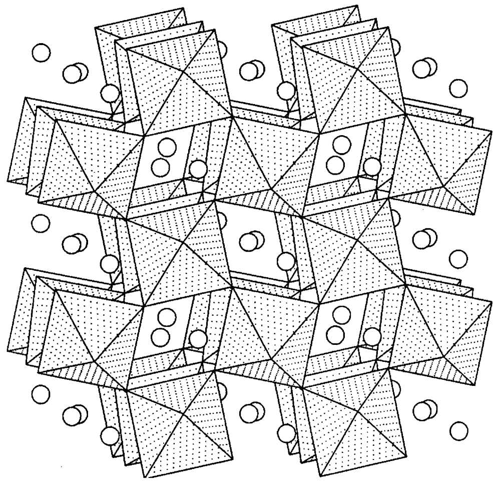


Figure 3.1.2-3: A perspective c–axis projection of $MgSiO_3$ in the perovskite structure. Si is in six–fold coordination with oxygen, which is shown as corner–sharing octahedra. Mg atoms are shown as circles, and are in eight–fold coordination in the interstices between octahedra.

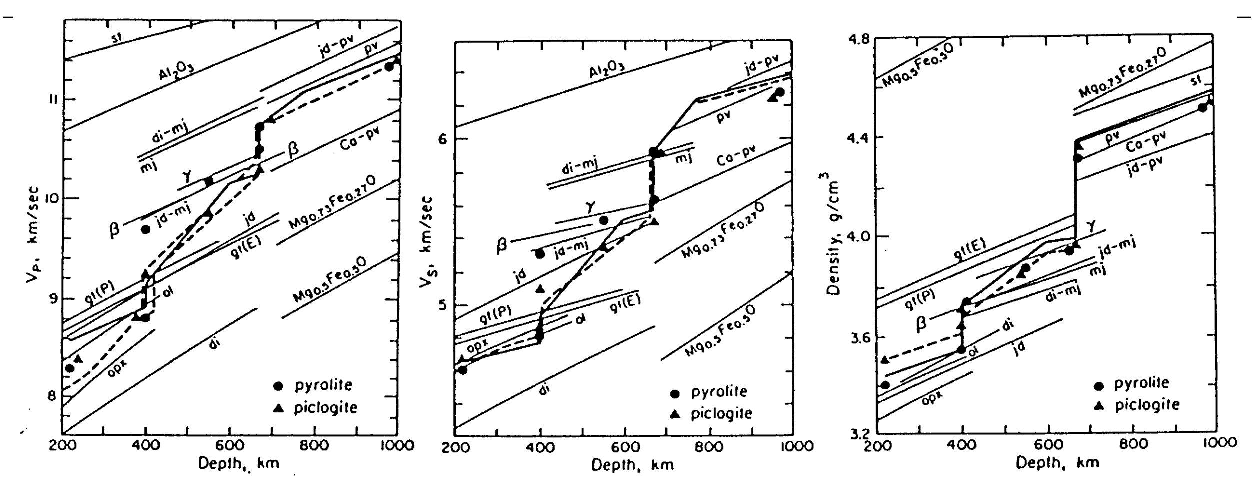



Figure 3.1.2-4: Comparison of globally averaged models for upper mantle P velocity (left), S velocity (middle) and density (right) with various experimental results for minerals and mineral assemblages. Such comparisons are used to interpret the velocity structures found by seismology.

### 3.1.3 Dynamical modeling of the deep interior

While decades of work have been directed at characterizing the chemistry and thermal properties of a static model of the Earth, much of the current excitement in the deep Earth sciences stems from the progress made in developing a model of the dynamics of the interior. This has awaited

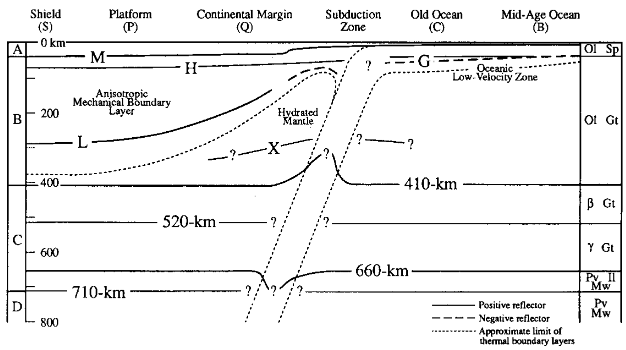



Figure 3.1.2-5: A highly schematized representation of the structure of the upper mantle inferred from seismic and mineral physics data, along a hypothetical cross section extending from a continental craton (left) across an active subduction zone (center) into an ocean basin (right). Tectonic regions are identified along the top. Discontinuities in the upper mantle are designated by a letter (M, H, G, L, X); those in the transition zone are designated by their average depth (410, 520, 660, 710 km). Possible major facies boundaries are shown on the right in a peridotitic composition. Ol, olivine; Sp spinel; Gt, garnet; $\beta$, beta phase of olivine; $\gamma$, gamma phase of olivine; Pv, perovskite; Mw, magnesiowüstite; Il, garnet in ilmenite structure.

the development of computer systems and programs capable of handling the massive computations required for three-dimensional flow models of the planet, as well as seismological and mineral physics constraints on the configuration and properties of deep materials. The Earth is a vigorous dynamic system, fueled by heat from accretion and later impacts, core formation, and radioactive decay. The active plate tectonic processes at the surface give testimonial to the deep seated motions and to the uniqueness of our planet in the solar system, but we still have limited understanding of the deep dynamic system.

Recent seismological and geochemical observations point to the need for realistic dynamic modeling of internal processes, as completely inconsistent models of the internal flow regime have been invoked to qualitatively explain the same data [e.g. Figure 3.1.1-6]. This includes fundamental issues such as the depth extent of lithospheric slab penetration, the source region and character of surface hot spots, and cartoon models of chemical reservoirs in the mantle. Even the absolute temperatures inside the Earth are poorly known due to our limited knowledge of the configuration of mantle convection. Until recently it has been impossible to actually test many of the scenarios that were advanced in various geophysical and geochemical interpretations, but now dynamic modeling capabilities are emerging that will allow realistic simulations to accompany most models. All areas of geophysical interpretation will be impacted by these new quantitative tools, but the development of dynamic modeling codes in turn requires direct input from various disciplines to ensure that the appropriate physics and material properties are included. Many fundamental processes such as melting and chemical differentiation at high pressure and temperature are at present very poorly understood, and it will therefore require strong interdisciplinary coordination in order to gain the ability of analyzing such processes quantitatively.

## 3.2 PHYSICAL AND CHEMICAL STRUCTURE OF THE DEEP EARTH

In order to appreciate the challenges that lie ahead in studies of the Earth's deep interior, it is important to first grasp the exciting progress and outstanding fundamental problems that have yet to be resolved. This section will give a brief overview of our current knowledge about the structure and composition of the deep system.

### 3.2.1 Large-scale structure of the mantle

Most of our knowledge of the detailed structure of the mantle has come from seismological procedures. Beginning in the 1930's seismologists began to develop Earth models for the first-order structure of the interior. In the past decade the emphasis has shifted to development of fully three-dimensional models. While this effort addresses the relatively small (few percent) internal fluctuations about an average radially symmetric model, these fluctuations have great importance as indicators of the dynamic configuration of the mantle. The inference of three-dimensional Earth structure from analysis of seismic data (termed "seismic tomography") has become a focus of intensive research efforts that have made rapid progress over the past decade.

The rapid progress in mapping three-dimensional mantle structure has occurred largely because of the accumulation of a sufficient quantity of high quality digital data from global networks that began operation in the mid-70's and continued to expand throughout the 1980's. This instrumentation development has been an international effort, with major contributions from France, Germany, The Netherlands, Japan, China, and many other countries in collaboration with the United States. By the end of this decade a complete upgrade of the global digital seismic network will have been largely accomplished and great quantities of new seismic data will be available for application to deep Earth investigations.

Over the last 25 years plate tectonics has provided the framework for understanding large-scale geological processes near the surface of the Earth. This theory describes the motion of large, rigid sections of the Earth's crust and uppermost mantle. The plates are transported by mantle convection currents, but a clear understanding of the exact relations between plate motions and convection in the underlying mantle has not yet been reached. Among the questions that remain unanswered is the depth extent of the flow associated with plate motions. Problems such as the existence of deep 'continental roots' or penetration of subducted material into the lower mantle are particular questions that arise within this context. Seismic tomography address these issues by mapping, in three dimensions, the seismic wave velocity variations in the mantle. These are related to temperature and composition variations and, consequently, to the density variations which provide the driving force of mantle convection.

Figure 3.2.1-1 is a cross-section in the equatorial plane through a recent whole mantle 3D shear velocity model. The principal features are two large regions of low velocity extending from the core-mantle boundary to, at least, the 670 km discontinuity. If one were told that the colors represent lateral variations in temperature, it would not be unusual to conjecture the picture to be a snapshot of mantle convection, even though some experts might be puzzled by the dominating presence of the very large wavelength field. While the seismic model has limited resolution, most of the heterogeneity in the lower mantle appears to be associated with large-scale features. There are other features of interest in the figure, in particular, the lack of continuity of some of the anomalies across the 670 km discontinuity.

Studies of the large scale three-dimensional structure of the mantle have been carried out using

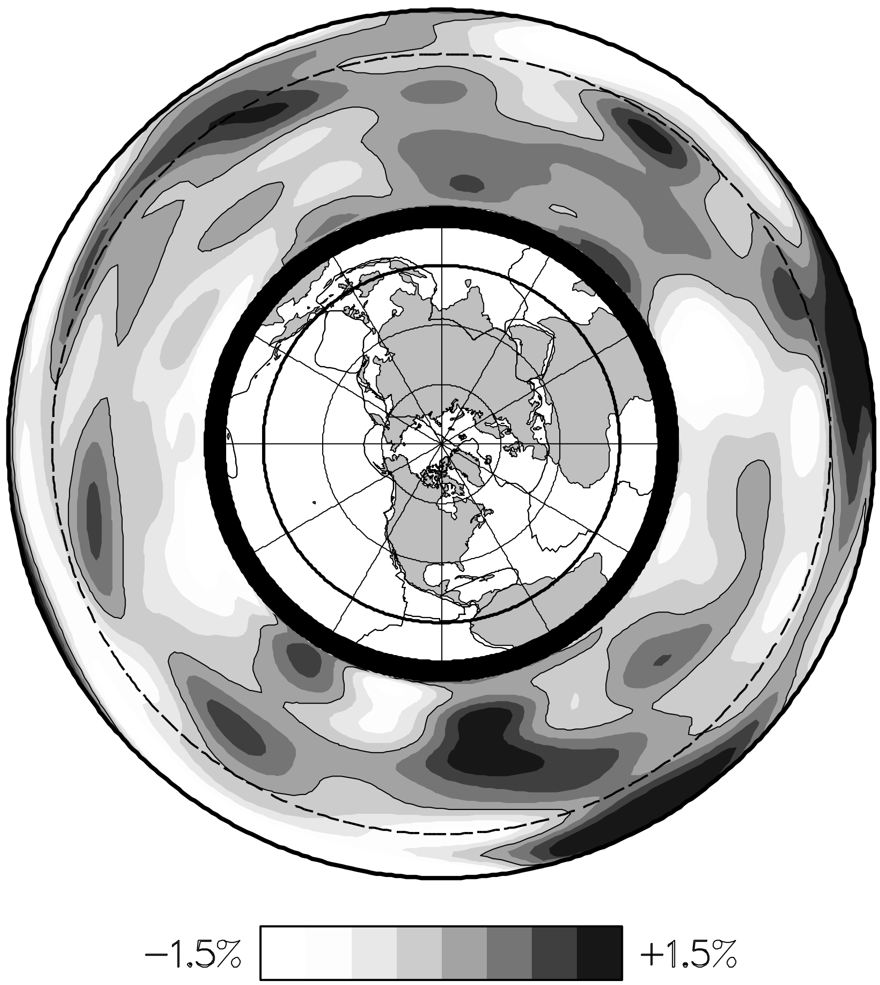



Figure 3.2.1-1: A cross–section through the equatorial plane of the whole-mantle 3D shear velocity model sh12wm13. The great circle defining the cross-section is identified by the thicker equatorial line on the inset map. There is no distortion of the horizontal or radial length scales in the cross–section. The range of the relative velocity perturbations indicated by the scale is +1.5%. Higher than average velocities are shown as dark and lower than averages velocities are shown as light.

various kinds of seismological data, spanning more than three orders of magnitude in frequency (1Hz - 0.0005Hz). These include P wave travel times, velocities and amplitude anomalies of surface waves, frequencies of spectral peaks of fundamental modes, complete waveforms of mantle waves, waveforms of long period body waves and complete spectra of split multiplets in the Earth's free oscillation spectrum. Seismologists are working toward a goal of extracting all structural information from the ground motion recordings.

Surface waves have yielded models of upper mantle S-velocity, revealing that the heterogeneity is most pronounced in the uppermost 250 km, and has a strong association with surface tectonic features above 150 km that diminishes with depth [Figure 3.2.1-2]. Important discoveries have included the patterns of deep fast velocity heterogeneity beneath continents and the dominance of long wavelength heterogeneity at all depths. The latest generation of surface wave models has

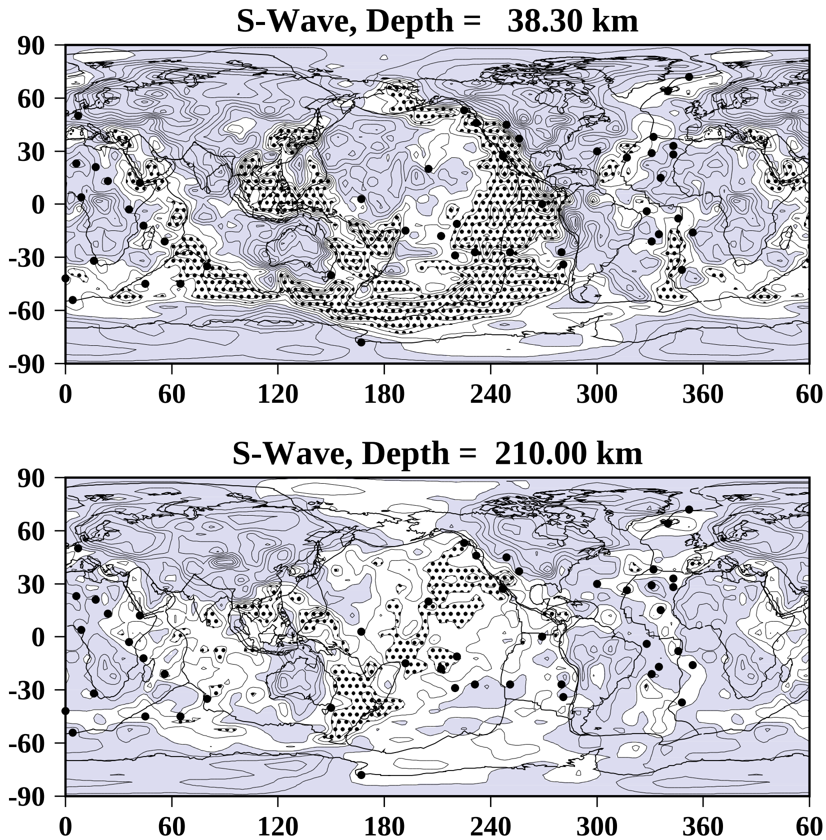



Figure 3.2.1-2: High resolution seismic tomographic models for upper mantle shear velocity structure near depths of 38 and 210 km. Faster than average regions are shaded. Slower than average regions are white, with dotted regions being slowest.

sufficient resolution to allow the deep structure of plate tectonic processes to be studied for the first time, with structure beneath ridges [Figure 3.2.1-3] and hotspots [Figure 3.2.1-4] revealing aspects of the deep plumbing of these regions. At present these models only have lateral resolution of about 1000 km, with vertical resolution of about 100 km, so many key tectonic features are not yet resolved. Body wave studies have provided higher resolution of localized regions, revealing that there are strong concentrated heterogeneities that are being smeared out in the long-wavelength models.

Body waves and surface wave overtones are used to determine structure in the transition zone, from 400-670 km deep. Transition zone heterogeneity is much more subdued than the uppermost mantle variations. It has been discovered that large-scale patterns in the transition zone have little resemblance to current surface tectonics, but good relationship with the cumulative history of subduction in the past 100 Ma. P wave travel time studies using large catalogs of seismic observations have revealed lower mantle P-velocity structure [Figure 3.2.1-5], which has only moderate heterogeneity throughout most of the mantle, but increased heterogeneity near the core-mantle boundary. With the addition of waveform modelling and free oscillations it has become possible to also constrain lower mantle S-velocity structure. The S velocities also reveal enhanced heterogeneity near the

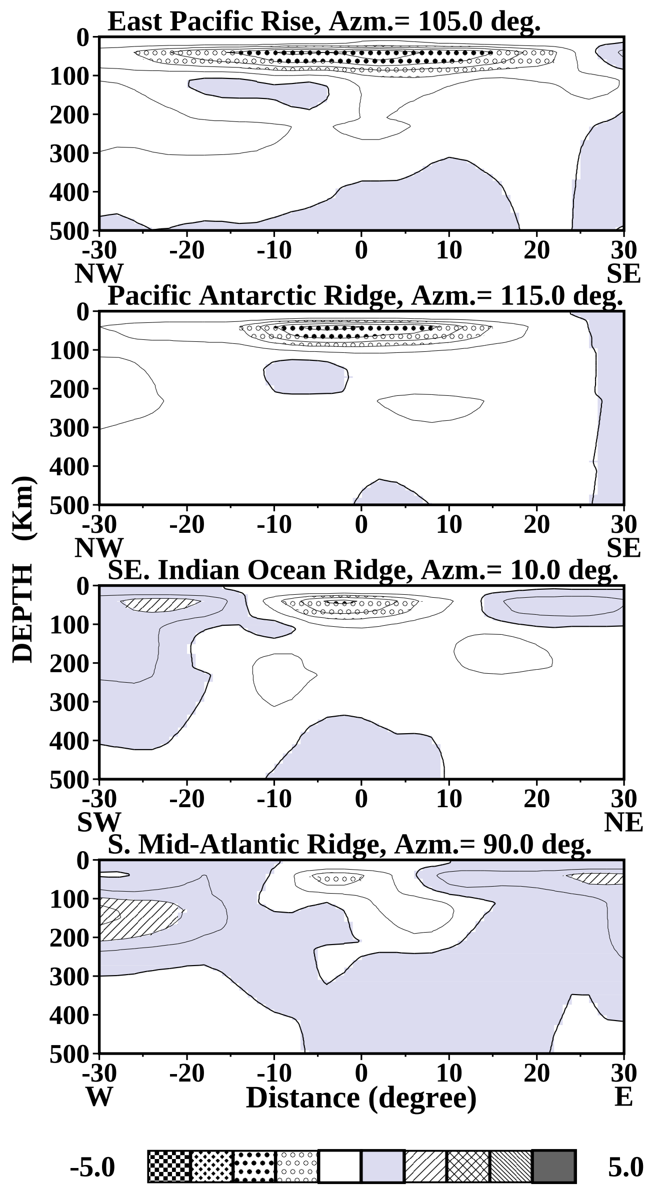



Figure 3.2.1-3: Depth slices of S-wave velocity variations for four ridges. From top to bottom: East Pacific Rise, Pacific-Antarctic Ridge, Southeast Indian Ridge and the southern mid-Atlantic Ridge. The ridge axes are aligned along the center. Note that the low velocity anomalies under ridges are concentrated above 100 km.

core-mantle boundary, indicative of a major boundary layer. Ongoing efforts are striving to improve the resolution of all of these models, and eventually to accumulate validated structures into a global model for the Earth.

At present, the best-resolved features of the lower mantle structure are only the very long-wavelength patterns. Figure 3.2.1-6 compares large scale components of P and S wave models for the deep mantle derived from different data sets using different analysis procedures. The general spatial

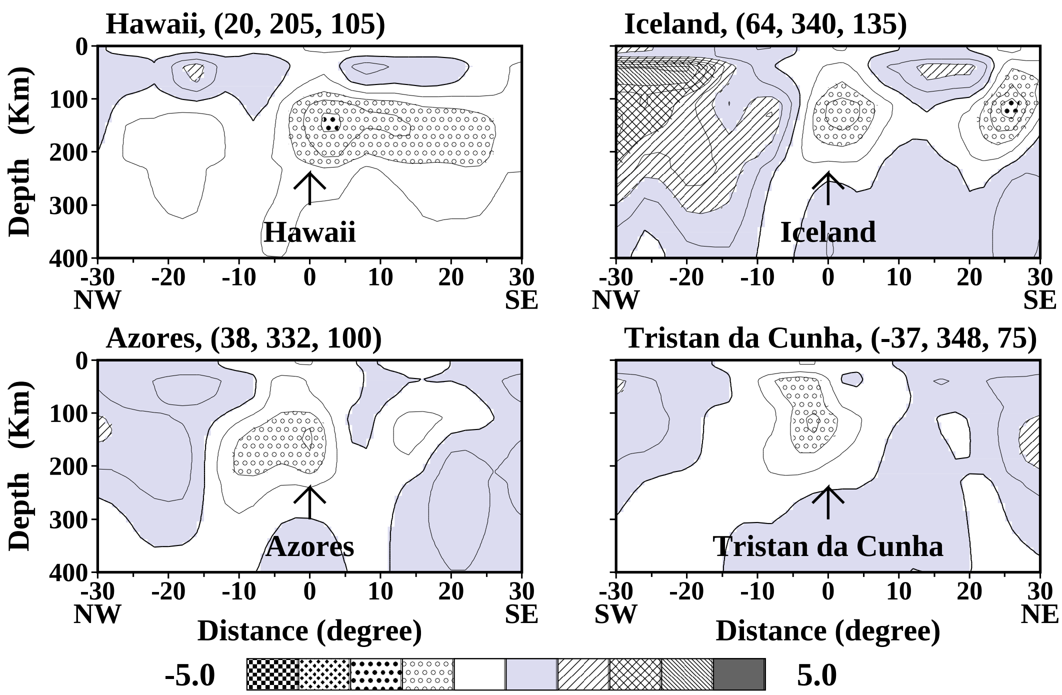



Figure 3.2.1-4: Depth slices at four hotspot locations. The abscissa shows the great- circle distances. Numbers above each plot indicate the latitude, longitude and azimuth of the great-circle at the hotspot. Note that low velocity anomalies under the hotspots are at depths of 100-200 km.

pattern in each data set is characteristic of the large scale structure in the lower mantle below 1500 km depth. This is generally characterized by a nearly continuous band of high velocity material extending below the Pacific Ocean margins. This type of comparison provides a valuable check on the various modelling techniques and allows a comparison of heterogeneity in different properties in the same region. Using one kind of data alone, it is often difficult to completely rule out the possibility that systematic errors or deficiencies in coverage, which are inherent in the data, degrade or corrupt the resulting models.

Tomographic studies sometimes require multi-year efforts to gather the data sets and derivation of models involves complex, multi-stage operations which often include subjective assumptions. There is an important need and opportunity to derive the maximum benefit from efforts of different research groups specializing in global tomography.

Figure 3.2.1-7 compares maps of relative velocity anomalies near the core mantle boundary. Panel (*a*) is a map of P-wave velocity perturbations obtained from the analysis of travel time residuals from the ISC Bulletins. Panel (*b*) is layer 11 of a degree-6 shear velocity model derived from by inversion of waveform data. Panel (*c*) is also the deepest layer of a degree-8 model obtained by inversion of absolute (S) and differential (SS-S and ScS-S) travel times. Panel (*d*) is a map of shear velocities at a depth of 2700 km computed from the a degree-12 model obtained by a joint inversion of waveforms (mantle waves and long-period body waves) and absolute (S, SS) and differential (SS-S, ScS-S) travel time data.

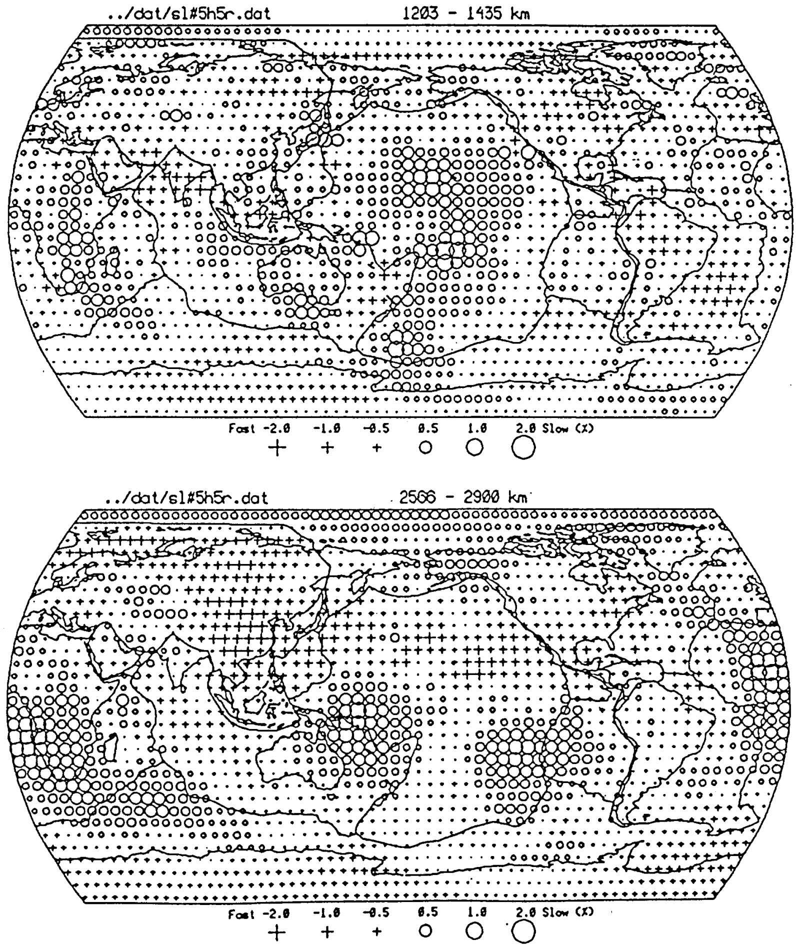



Figure 3.2.1-5: Maps of the P velocity variations at two depths in the lower mantle, obtained by seismic tomography. Circles indicate slow velocity regions.

All four panels show the same main features: the ring of fast velocities around the Pacific and slow velocities and large areas of slow velocities under the Pacific and Africa. There are differences, of course. Some of them may be real: P-velocities are mapped in panel (*a*), while the remaining three panels show shear velocity anomalies. There is no reason to expect that only a constant scale factor should be applied to map one parameter into the other. Of the three S-velocity panels the last two are fairly similar both in pattern and amplitude, perhaps because a part of the data sets used in inversion is common.

This illustrates the benefits to be derived from multi-institutional efforts supported by CSEDI initiative. The subsets of the data set used to derive the model in panel (*d*) were derived in different institutions; in this case this intellectual merger was accomplished through a traditional route of a graduate student becoming a post-doc at another university.

Figure 3.2.1-8 demonstrates the need for joint efforts to resolve controversies that may impede progress in a variety of applications of seismic tomography. The top panel is a map of shear velocity anomalies at a depth of 200 km from a recent high resolution surface wave study; the same model was already shown in Figure 3.2.1-2. The bottom panel is a degree-12 model derived through

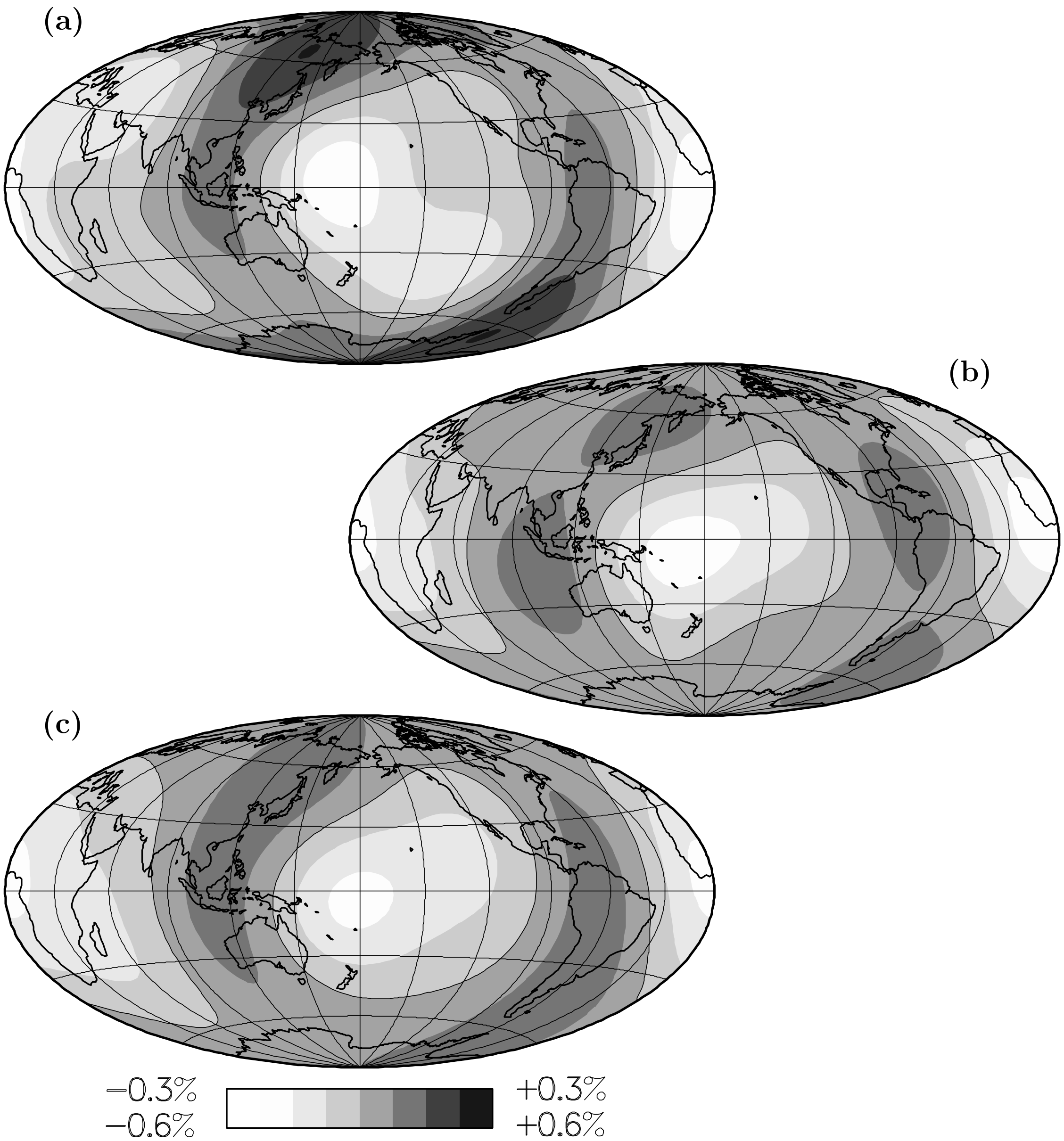



Figure 3.2.1-6: Comparisons between different tomographic models obtained from different data sets with different procedures. (a) P velocity model V3.I, degrees 2 and 4 only at 2300 km, range is +0.3%. (b) S velocity model U84L85/SH at depth 2300 km, degrees 2 and 4 only, range is +0.6%. (c) S velocity model based on free oscillation data, depth 2300 km, degrees 2 and 4 only, range is +0.6%.

a joint inversion of the waveform and travel time data.

There is significant difference between the two models in the overall amplitude of the anomalies at this depth. Even though the basic pattern — oceans are slow, continents are fast — is the same in both maps, there are important differences in detail. In particular, the slow anomalies associated with the mid-ocean ridges are not readily identifiable in the top panel, while they are continuous features in the bottom panel. The differences between the two models increase with depth and

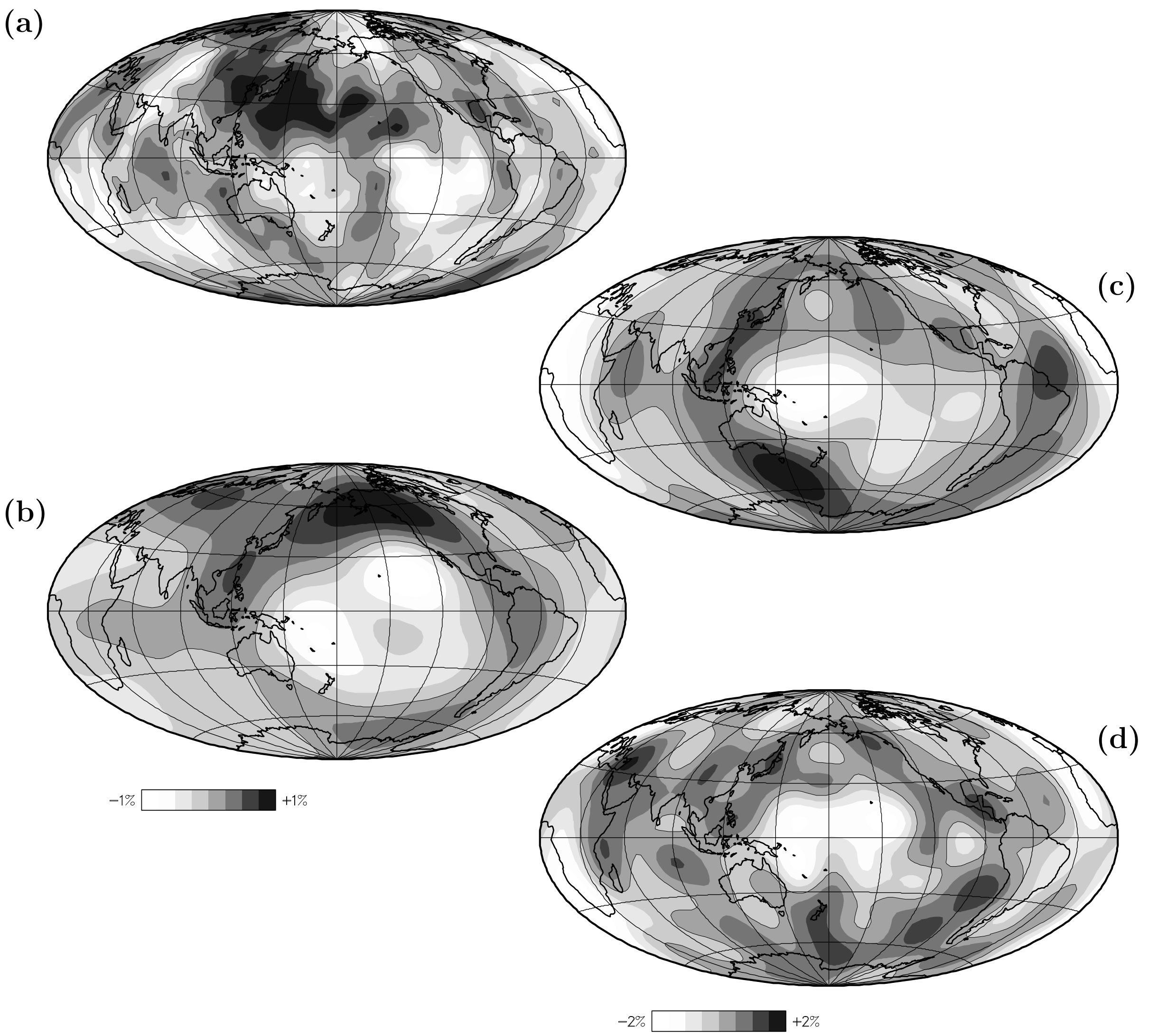



Figure 3.2.1-7: Comparison of four 3-D models just above the core-mantle boundary. *a).* Layer 16 (2566–2900 km) of a P-velocity model of Inoue *et al.* (1990). *b).* Layer 11 (2630–2891 km) of degree-6 S-velocity model of Tanimoto (1990). *c).* Layer 11 (2630–2891 km)of a degree-8 S-velocity model of Masters and Bolton (1991). *d).* Degree-12 S-velocity model of Su *et al.* (1992) at a depth of 2850 km. Note that the scale range is ±1% for the panels *a)* and *b)* and ±2% for panels *c)* and *d).*

have significant implications with respect to the origin of the mid-oceanic ridges (*e.g.* passive *vs.* active features).

The situation here is more complex because of the very different approaches to the data analysis and interpretation used by the two research groups. In this case it is doubtful that simple merging of the two data sets would resolve the controversy. Perhaps, CSEDI could sponsor a series of agreed upon experiments, some of which may require substantial effort, that would identify the cause of the discrepancy.

An important result of the various tomographic studies is that the heterogeneity throughout the

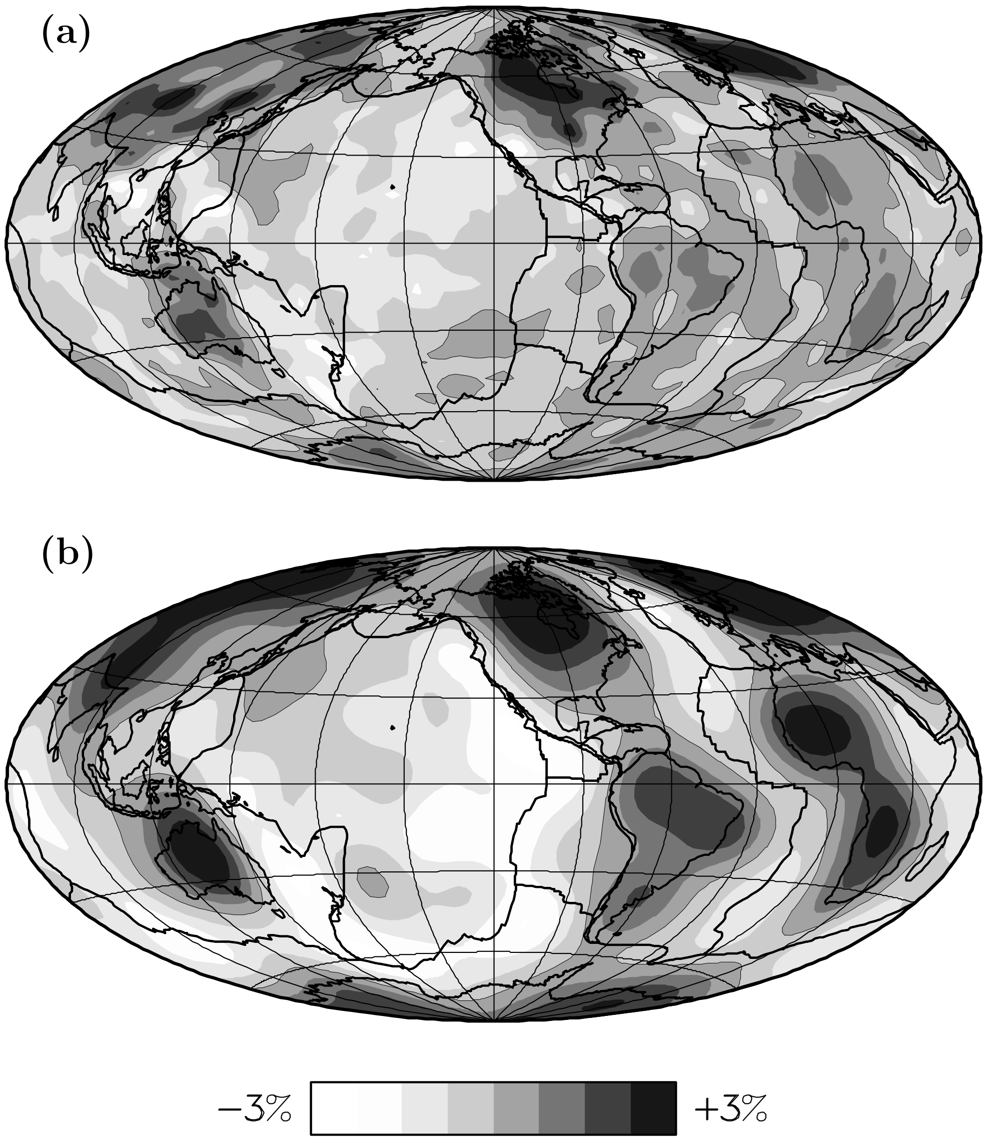



Figure 3.2.1-8: (a) degree-36 shear velocity model of Zhang (1991) at a depth of 210 km. (b) degree-12 shear velocity model of Su *et al.* (1992). The zero contour is shown as a thin continuous line. Note the higher amplitude of the degree-12 model and the fact that for that model the mid-oceanic ridge anomalies are still clearly visible at this depth, while the East Pacific Rise and Mid-Indian Rise are not anomalous in the model of Zhang.

mantle appears to have a relatively red spectrum, with most of the power concentrated in large scale fluctuations. This is fortunate in that it allows relatively unbiased models of the large-scale structure to be developed first.

Such large scale heterogeneities are clearly not the whole story, however, for we know that smaller scale heterogeneities exist in some places. For example, large scale tomographic models indicate slow seismic velocities near subduction zones, but we know that cold (hence high velocity) material is descending into the upper mantle in these regions. It is likely that the slow velocities are due to back arc spreading, but in any event important smaller scale heterogeneities are not apparent in

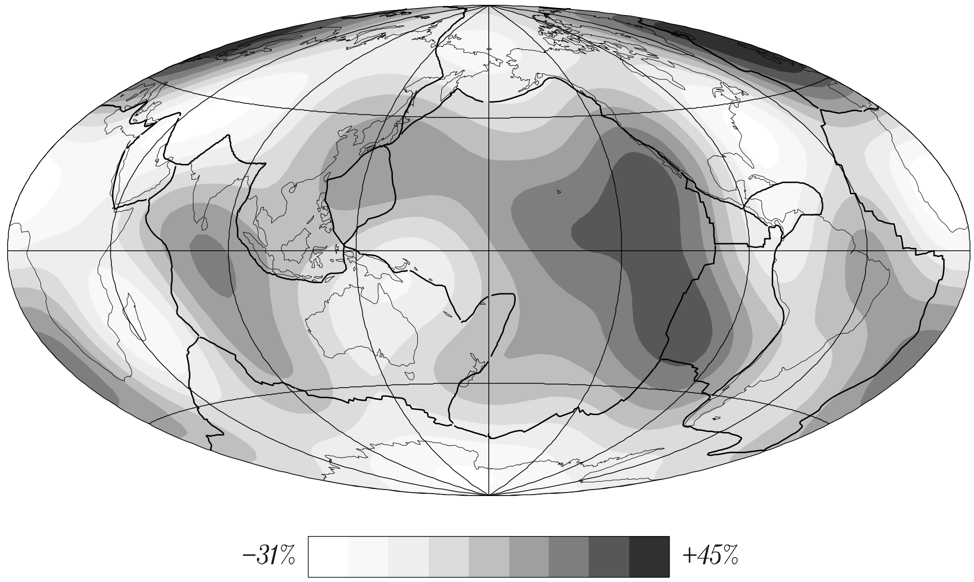



Figure 3.2.1-9: Inferred lateral variations of attenuation of seismic waves at a depth of 160 km in the mantle. Such lateral variations are presumably related to lateral temperature variations or the presence of small amounts of partial melt. The attenuation is very high in the Eastern Pacific near the East Pacific Rise, as well as along the Mid–Atlantic Ridge. Such variations in attenuation may affect the interpretation of measured seismic velocities in terms of laboratory measurements at higher frequencies, as well as comparisons between seismic velocity variations and density variations related to the geoid.

the larger scale models. Thus, attaining higher resolution in the seismic models of the mantle is an important objective.

The simplest interpretation of the seismic velocity heterogeneity of the mantle in terms of temperature variations and mantle dynamics follows from the association of low seismic velocities observed beneath mid-ocean ridges (hot regions associated with upwelling and partial melting) and high seismic velocities beneath old oceanic lithosphere and beneath continental shields (associated with cooling of the lithosphere and upper mantle). This suggests that the seismic structure is related to large scale convection associated with plate motions. There are, however, indications that the situation may not be so simple. The high seismic velocities beneath continental shields may reflect differences in composition and mineralogy; such differences may exist throughout the mantle, and an interpretation of seismic velocity variations solely in terms of temperature may be incorrect.

Given the ambiguity of interpreting seismic velocity variations it is important to compare them quantitatively with other observations or data. The earliest such efforts related the seismic structure to density anomalies and hence the geoid; this ultimately led to the realization that density anomalies in a non-rigid mantle must be dynamically supported, and has led to models that account for a large part of the Earth's nonhydrostatic geoid on the basis of the seismic models together with particular models of mantle rheology [Figure 3.1.1-6]. The essence of such models is flow driven by density variations, which are inferred from the seismic velocity variations. A number of other phenomena have also been investigated, such as the topography of the core- mantle boundary and the surface, plate motions, and convective heat transport. For example, core-mantle boundary topography induces coupling between the core and mantle, thus the magnitude of the topography in seismic models can be related to changes in length of day.[Figure 3.3.3-1]

The currently available tomographic models of the mantle are by and large purely elastic models in that they either ignore anelasticity or they rely on a predefined spherically symmetric anelastic model. Nevertheless, large lateral variations of Q in the deep mantle are know to exist, and are intriguing, since attenuation is frequently associated with temperature variations or the presence of fluids. Evidence for lateral variations in excess of 50% in the upper mantle has been obtained from the analysis of normal mode and surface wave data , and multiple ScS attenuation data indicate variations of as much as 100%, some of which could originate in the lower mantle. Retrieving Q estimates from the measurement of amplitude of body and surface waves is a much more complex problem than that of measuring shear velocity. This is primarily due to the difficulty of separating effects of intrinsic attenuation from strong and nonlinear effects on amplitudes due to propagation in a laterally heterogeneous elastic earth. It is only recently that, with theoretical progress and the availability of high quality digital data, we have been able to start addressing the question of 3D Q structure in the mantle. Figure 3.2.1-9 illustrates the kind of resolution presently achievable for Q in the upper mantle, a resolution comparable to that of the first tomographic models of the early 1980's. There is a good correlation of Q with tectonics and elastic velocities in the upper 200 km of the mantle, with amplitudes of lateral variations in excess of 40%. Below that depth, the pattern changes and, as for velocities, a strong degree two pattern emerges. The relation to the elastic structure indicates that lateral variations in shear velocity are most likely primarily of thermal origin.

There are uncertainties and limiting assumptions that affect all of the seismic models that have been produced. Some of these arise from the data, which are limited in spatial coverage and contain noise; others arise from assumptions made in order to analyze the data in terms of a seismic model, such as assuming elastic isotropy, or limiting a seismic model to only large scale variations. These uncertainties are evidenced by the evolution of seismic models as more data is brought to bear, and as different assumptions and techniques are used to interpret the seismic observations.

### 3.2.2 Geochemical and petrological structure of the mantle

Seismology yields only a limited characterization of the material properties of the Earth's interior. Much additional information is required before the composition and dynamics of the deep Earth can be determined. To illustrate the problem, we can consider a tomographic image of the mantle as a snapshot of the current structure of the interior, perhaps reflecting variations in temperature inside the Earth. Yet rock has a long thermal "memory", due to its low thermal conductivity, so the tomographic images largely reflect older, not present-day, tectonic motions that created the temperature variations now being imaged. Also, such interpretations depend upon our ability to separate different causes for the velocity variations: in addition to variations in temperature, variations in rock type (e.g., bulk composition, mineralogy and texture) and in the amount of water or hydrated minerals present can strongly influence the observed velocities. Clearly, we need 'ground truth' as a platform for any interpretation of the chemistry of the deep interior.

Examination of rock samples derived from the outer 50-200 km of the Earth has established that the primary minerals present in the uppermost mantle are 50-60% $(Mg,Fe)_2SiO_4$ olivine, 20-40% $(Mg,Fe,Ca)SiO_3 : Al_2O_3$ pyroxene, and 10% $(Mg,Fe,Ca)_3Al_2Si_3O_{12}$ garnet, with the ratio of Mg/(Mg+Fe) components being about 0.9 for the upper mantle assemblage. The compositions and volume fractions listed are approximate, but encompass over 98% of the estimated average composition of the upper mantle on an atomic basis. This assemblage of minerals comprises the

## MANTLE PHASES

| Pressure (GPa) | OLIVINE COMPONENT | PYROXENE–GARNET COMPONENT | Depth (km) |
|---|---|---|---|
| 0 — | | | — 0 |
| | Olivine<br>$^{VI}(Mg,Fe)_2^{IV}SiO_4$ | Pyroxene + Garnet<br>$^{VI}(Mg,Fe,Ca)^{IV}SiO_3 + {}^{VIII}(Mg,Fe,Ca)_3^{VI}Al_2^{IV}Si_3O_{12}$ | |
| | | | — 200 |
| 10 — | | | |
| | $\beta$–phase | Garnet–Majorite<br>$^{VIII}(Mg,Fe,Ca)_3^{VI}[(Mg,Fe)SiAl_2]^{IV}Si_3O_{12}$ | — 400 |
| | $\gamma$–Spinel | Ilmenite<br>$^{VI}(Mg,Fe,Ca)^{VI}(Si,Al)O_3$ | |
| 20 — | | Perovskite<br>$^{VIII-XII}(Mg,Ca)^{VI}(Si,Fe,Al)O_3$ | — 600 |
| | Magnesiowüstite + Perovskite<br>$^{VI}(Mg,Fe)O + {}^{VIII-XII}(Mg,Ca)^{VI}(Si,Fe,Al)O_3$ | | |
| | | | — 800 |
| 30 — | | | |

Figure 3.2.2-1: Summary of the predominant mineral phases existing in the outer 800 km of the mantle, shown as a function of pressure (left-hand scale) and corresponding depth (right-hand scale). The lower -pressure phases are put into two groupings, the olivine component and the pyroxene component, and the high pressure assemblage is dominated by the silicate perovskite phase. The coordination numbers for the cations are given in roman numerals within the chemical formula for each phase, demonstrating the increase in cation coordination with pressure. The structural chemical formulae for $\beta$–phase and $\gamma$–spinel are identical to that of olivine, and both orthopyroxene and clinopyroxene are represented by pyroxene.

rock type peridotite, of which peridot (the gem variety of olivine) is the predominant phase.

There is increasing uncertainty in the bulk composition and volume fractions as one goes deeper into the mantle, primarily because we have very few direct samples. It is well known that the olivine, pyroxene and garnet minerals found in the upper mantle will undergo phase transformations with increasing pressure and temperature, so the form of any corresponding deep mantle components can be anticipated, even in the absence of actual 'hand-samples'. For example $(Mg, Fe)_2SiO_4$ olivine transforms to a spinel polymorph, b-phase, at presures near 10 GPA, or a depth of 400 km. Olivine further transforms to the spinel g-phase at somewhat greater pressures, corresponding to depths near 520 km. The general characteristic of these transformations is that the coordination of oxygen around cations increases with pressure. Olivine subsequently undergoes a further transformation into a dense perovskite structure phase in combination with magnesiowüstite near a pressure of 25 GPa. Similar transformations occur in the pyroxene-garnet components in the upper mantle [Figure 3.2.2-1].

A major uncertainty in many of these reactions is the role of hydrogen or water. There are several hydrous magnesian silicates that are stable at pressures greater than 10 GPa, although most have

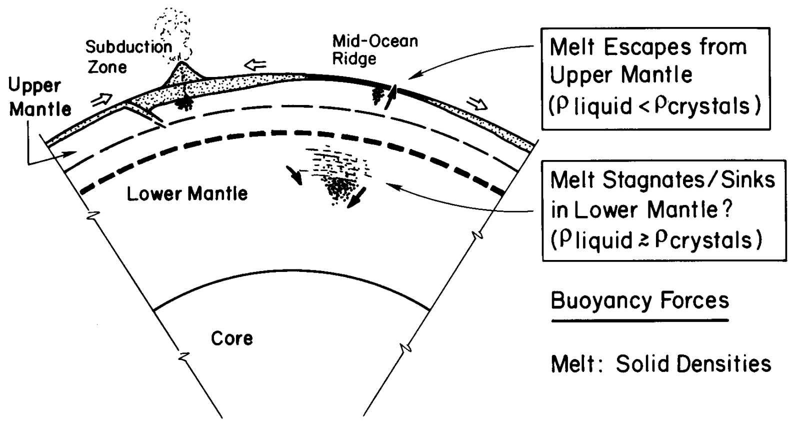



Figure 3.2.2-2: Schematic illustration of mantle convection leading to plate tectonics at the surface (open arrows). Partial melting in the uppermost mantle creates liquid that rises to the surface (solid arrow) because the melt is less dense than the surrounding rock. The result is that volcanic eruptions occur at mid-ocean ridges, forming new oceanic crust, and at subduction zones. In the lower mantle, melts tend to be neutrally buoyant and may even sink (solid arrows) thus impeding geochemical differentiation and upward transport of heat by magmas (the top of the lower mantle is indicated by the bold dashed curve).

Mg/Si ratios greater than 2 and so may not be important phases. Perhaps more significantly, minor amounts of hydrogen may selectively enter some of the nominally anhydrous phases causing some uncertainty in the experimentally determined phase boundaries, although the phase boundaries are fairly well established for the anhydrous peridotite compositions.

Thus, even if the upper mantle is primarily peridotitic, there is a complex suite of mineral phases in the upper mantle. Lateral variations in temperature and volatile content will produce a great proliferation of phase boundaries within the upper mantle, compounded by additional chemical heterogeneity. However, the peridotitic components of the lower mantle are in a relatively simple assemblage dominated by silicate perovskite. Experimental work has shown that silicate perovskite is stable throughout the pressure range of the lower mantle, indicating that $(Mg, Fe)SiO_3$ perovskite is the most abundant mineral inside the Earth, making up over 40% of the planet. This is in accord with the seismological observation that the density and elastic properties of the mantle vary smoothly between depths of about 800 and 2500 km.

If the entire mantle is actually uniform in composition, we already have a good understanding of its various mineral phases. However, there are good reasons to question how the complex, ongoing differentiation process of the interior could yield a uniform composition at present. Resolution of any chemical stratification in the mantle requires a synthesis of information from many disciplines, as the deeper layers may intrinsically be sealed from surface sampling. It is also necessary to explain the existence of long-persisting distinctive geochemical heterogeneities or reservoirs in the deep mantle. As our aim is to understand the processes by which the interior evolves, we must understand the properties of the materials making up the crust, mantle and core, and the ways in which these materials can be altered with time. A case in point is geochemical differentiation, the means by which compositionally distinct regions of the Earth are produced and arguably the single most important process defining the geological evolution of a planet.

It is generally accepted that the only mechanism by which differentiation can proceed on a large scale (e.g., creating a distinct crust and mantle) is through partial melting. Upon melting, the liquid that is produced typically differs greatly in bulk- and trace- element composition from the starting material, the"source rock". Also, because its viscosity is some 10-20 orders of magnitude lower than that of the surrounding rock, the melt can rapidly migrate or percolate to a new region.

Global-scale differentiation can proceed in this manner, the upward migration of melts from the mantle causing volcanism at the Earth's surface. The close association of volcanism with tectonic setting and heat loss from the interior, as encapsulated by the plate-tectonic theory, highlights the underlying significance of geochemical differentiation on the global scale. Yet we now recognize that molten rock, magma, does not necessarily rise toward the surface. Indeed, recent experiments demonstrate that deep in the upper mantle (depths km depth), the densities of typical magmas are comparable to or exceed that of the surrounding rock [Figure 3.2.2-2]. That is, the melts are either stagnant or actually sink throughout much of the Earth's interior: the differentiation process, and the attendant transport of heat by the magma, occurs in a manner that is completely different than is observed in the near-surface geological environment. It is only with a knowledge of such fundamental variations in processes within the planet that geophysical observations of the interior properties can be reliably interpreted.

Clearly, the geophysical observations of the internal structure and our understanding of interior processes obtained through laboratory, theoretical or field-observational research, must be put in the context of the geochemical constraints on the Earth's internal history. At present, we are on the verge of being able to proceed with such a program: having recently developed significant new ways of documenting the processes and actual history of the planet's geological evolution, we are at the exciting point of being able to bring these new observations together into a unified picture.

One of the major hurdles we currently face in bringing together the detailed observations that we have on the mantle is to better understand the physical and petrological meaning of the geochemical reservoirs: How many reservoirs are there? How, exactly, are they formed and how can they be destroyed by re-mixing? Are there clear-cut geophysical anomalies associated with particular reservoirs (e.g., ocean-island basalt source)?

To answer these questions will require a multi-disciplinary approach involving researchers in petrology, geochemistry and various aspects of geophysics. For example, the initiation of partial melting, the process by which a geochemical reservoir begins to form, is poorly understood, both in physical and chemical terms. Similarly, the geodynamic or fluid dynamic processes of mixing and recycling of existing heterogeneities are not well established, and we are uncertain what seismological heterogeneities (or other geophysical anomalies) we might expect to observe.

Even a basic question such as "Is the lower mantle partially molten at present?" is unresolved. However, major advances have recently been made in geophysical, geochemical and petrological observation and theory, so we have good reason to believe that global processes by which the mantle evolves can now be brought into sharp focus.

### 3.2.3 The transition zone

As Francis Birch once remarked, the transition zone is the key to the evolution of the mantle. The transition zone, at depths of 400-650 km, deserves special attention because observations of this region will answer what is arguably the most important question in geodynamics: is mantle convection layered or not? [Figure 3.2.3-1] Slabs sink easily into the transition region but resist

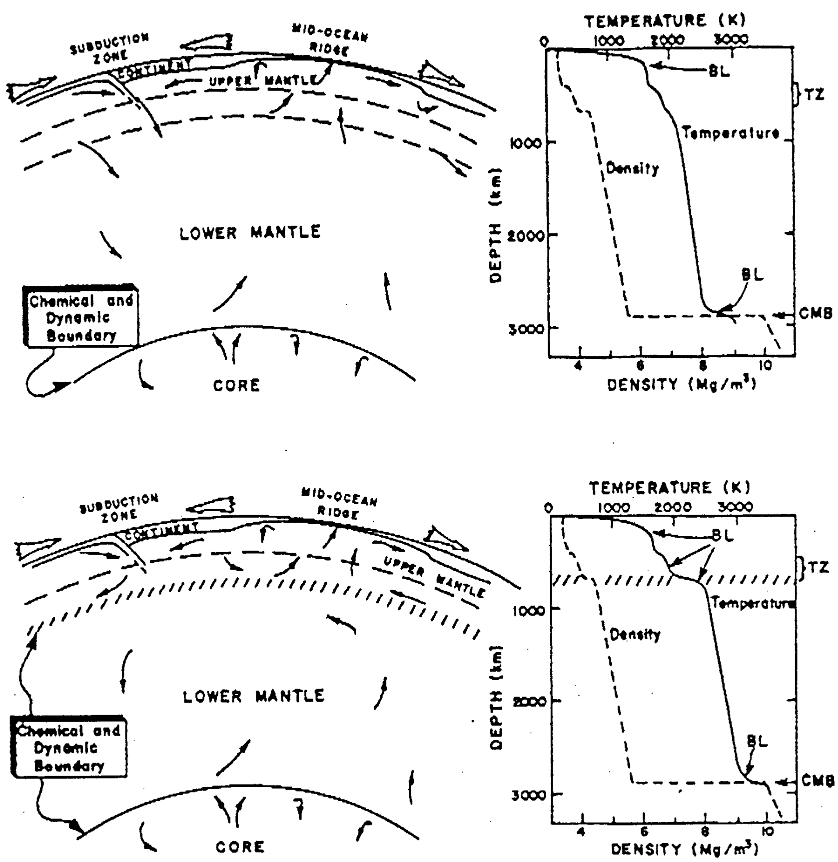



Figure 3.2.3-1: Two possible models of the mantle: uniform in composition and homogeneously mixed (upper panel) or stratified into separately convecting upper and lower regions (lower panel). Observed density and calculated temperature distributions as functions of depth are shown on the right. Stratification can occur due to a change in composition (chemical boundary) which prevents the lower mantle from being mixed into the upper mantle. As a result, thermal boundary layers (BL) occur at the base of the transition zone (TZ) and higher temperatures are reached at the core- mantle boundary (CMB) than in the case of uniform composition.

sinking through the 650 km discontinuity. A negative Clapeyron slope, an increase in viscosity, or an increase in intrinsic density can all slow down or stop a slab from penetrating further.

Resolving the pattern of convection within the mantle is clearly significant if we are to understand the detailed forces underlying plate tectonics at the surface. Moreover, the pattern determines the long-term thermal evolution of the planet. That is, if the upper mantle convects separately it would act as a blanket that thermally insulates the lower mantle. The timescale of thermal evolution, and therefore of geological activity, for the planet would consequently be increased tenfold or more, compared with an unlayered scenario in which the entire mantle is mixed by convection. Finally, if mantle convection is layered, the lower mantle (the bulk of the planetary interior) is fundamentally inaccessible to us as geological samples, because rock from depths below the transition zone would never reach the surface.

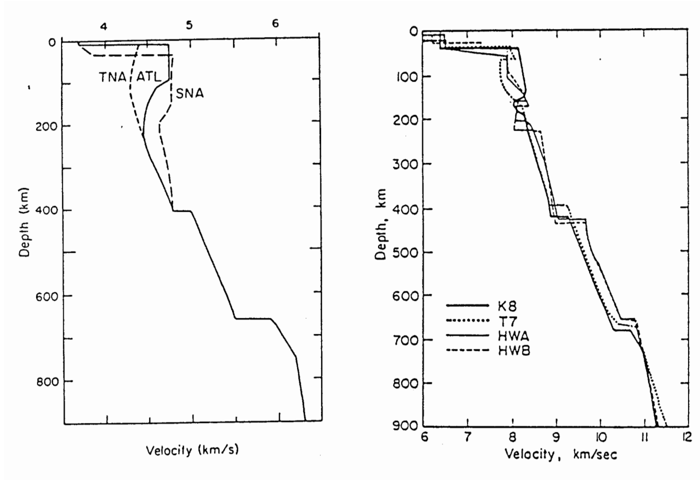



Figure 3.2.3-2: A variety of S wave (left) and P wave (right) velocity models determined in different regions by waveform modeling of upper mantle seismic triplication arrivals. Models with higher velocities (SNA,K8) correspond to upper mantle beneath stable shield. Models with lower velocities (TNA, T7) correspond to tectonically active regions. Note that there is little variation below 400 km depth.

The characteristic feature of the transition zone is that pressures are sufficiently high in this region that the common minerals of the upper mantle transform to new, dense phases. Such mineral transformations are well established from laboratory experiments, and they provide a good explanation for the abrupt changes in seismic properties observed at ∼400–700 km depth [Figure 3.2.3-2]. Seismologists have developed many techniques to study the transition zone boundaries, characterizing their depths, sharpness (depth extent), velocity and impedance contrasts, and more recently the topography on the boundaries. This is possible because the contrasts in material properties at the boundaries give rise to reflected and converted phases [Figure 3.2.3-3] which can be unambiguously identified. Evidence for a globally extensive seismic boundary near 520 km has recently been discovered in the converted arrivals.

A major line of seismological evidence supporting the interpretation of the 410 and 660 km discontinuities as phase boundaries is their relative sense of topographic deflections. Figure 3.2.3-4 summarizes work on seismological reflections which are compatible with the experimental determinations of Clapeyron slope of olivine phase transitions for these boundaries. Given that the temperature sensitivity of the phase boundaries is fairly well determined experimentally, mapping the topography on the boundaries can provide a direct thermometer of transition zone structure. Figure 3.2.3-5 shows the first global map of topography on the 660 km boundary, displaying + 15 km topographic variations. Stronger deflections may occur on local scales. Regions of long-enduring subduction around the Pacific margin tend to have depressed 660-km discontinuities, consistent with the piling up of cold downwelling material in these regions.

The phase transformations at 410 and 660 km may obscure what is happening through the transition zone, however. For example, they may be masking a change in bulk composition between the upper and lower mantle, which would lead to layered convection. Furthermore, we only have a partial understanding of how the occurrence of phase transformations may affect mantle convection. Theoretical calculations show that the pattern of convection could be strongly influenced, depending

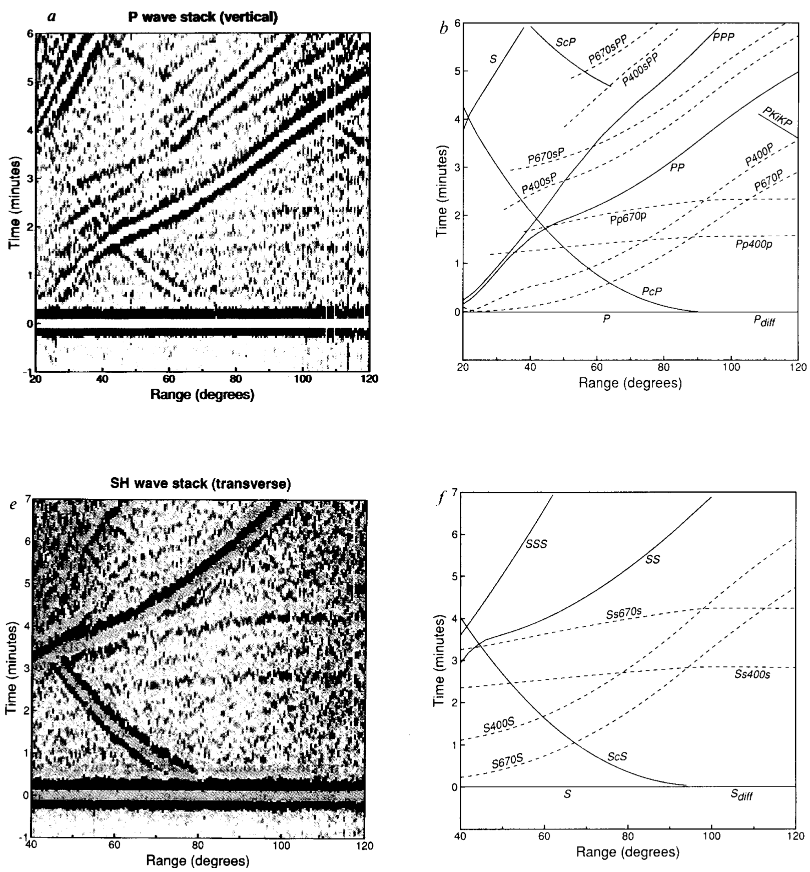



Figure 3.2.3-3: Observed seismogram profiles comprised of thousands of stacked waveforms at different distances. The upper figure is for vertical components aligned on the P waves, and the lower is for horizontal transverse components aligned on the S waves. Travel time curves are shown for model PREM, with arrival times of major seismic phases (solid lines) and minor phases generated by interactions with upper mantle discontinuities near 410 and 660 km depth.

on subtle changes in properties associated with the transformations.

One of the most exciting recent developments is the recognition that we have a few samples, volcanically ejected rock fragments, that come from the depths of the transition zone. Most such xenolith samples are from much shallower levels (¡ 200 km depth), but the question remains open whether there can be any samples from deeper levels. It is fair to say that samples from transition-zone depths, let alone deeper, are more rare than samples from the Moon, yet they can provide unique insights into the geological evolution of our planet.

The fate of slabs sinking to the transition zone is the subject of many seismological, geodynamical, and mineral physics investigations (see 3.4.4), and is still an unresolved issue. Similarly, we do not know whether mantle plumes originate from below the transition zone or not. The most popular hypothesis at present is that some if not most plumes do originate from deep within the lower mantle, perhaps as far down as the core-mantle boundary. If so, how is there ascent affected by the transition zone? Do all plumes make it through this region or does the transition zone act as a filter, allowing only certain types (e.g., compositions) of plumes to pass through and therefore giving us a biased sampling of the deepest mantle?

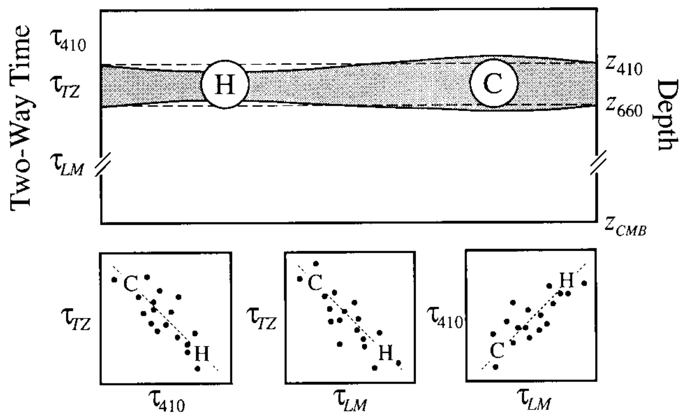



Figure 3.2.3-4: Schematic illustration of the model of thermally induced discontinuity topography used to explain the 10 s variations in shear wave travel time through the transition zone observed on a path by path basis. Because the discontinuities have Clapeyron slopes of opposite sign, they move together in warm regions, reducing the travel time between them. Although this is partially offset by the reduction of ambient velocity, the net result is a decrease in travel time through the locally warm region. The inferred long wavelength temperature anomaly is on the order of 200°C.

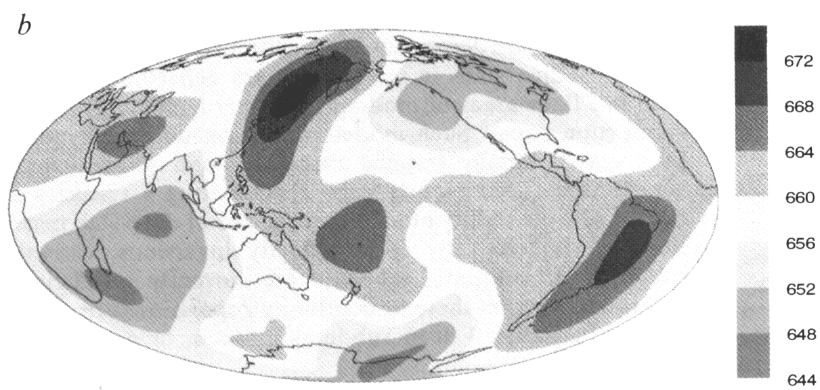



Figure 3.2.3-5: A smooth fit to the apparent depth of the 660-km discontinuity from SS precursors that reflect from below the boundary. The depths have been corrected for an upper mantle shear velocity model and are plotted relative to the mean depth of 659 km.

The important point is that several different approaches are now converging in giving us answers to these questions. High-resolution seismological studies are beginning to offer detailed images of slabs as they penetrate into (and through?) the transition zone; complementary imaging of plumes eventually should reveal where these important upwellings originate. At the same time, mineral-physics and petrological data are converging on reliably constraining the composition and state of the lower mantle: the question of layered or unlayered convection (different or identical bulk compositions for the upper and lower mantle) is steadily being resolved.

Finally, models of convection are becoming sophisticated enough to be able to address the geodynamic complexities of the transition zone. The effects of phases transitions and of lateral variations in properties (e.g., stiff slabs) can be accounted for; mixing and recycling are being quantified for the first time; and if the mantle is layered, we will be able to address the leakiness across the transition zone and intrinsic time-dependence of this system.

### 3.2.4 The core-mantle boundary

The boundary between the mantle and core has attracted considerable attention over the past few years. In particular, new geophysical observations, primarily from seismology, geomagnetism and geodesy, show that the lowermost mantle is extremely heterogeneous. In fact the lateral variations in properties near the core-mantle boundary exceed those found anywhere else in the Earth, except at the surface [Figure 3.2.4-1]. This is due to the role that the core-mantle boundary plays as a transition zone between vastly different chemical, thermal and dynamic regimes.

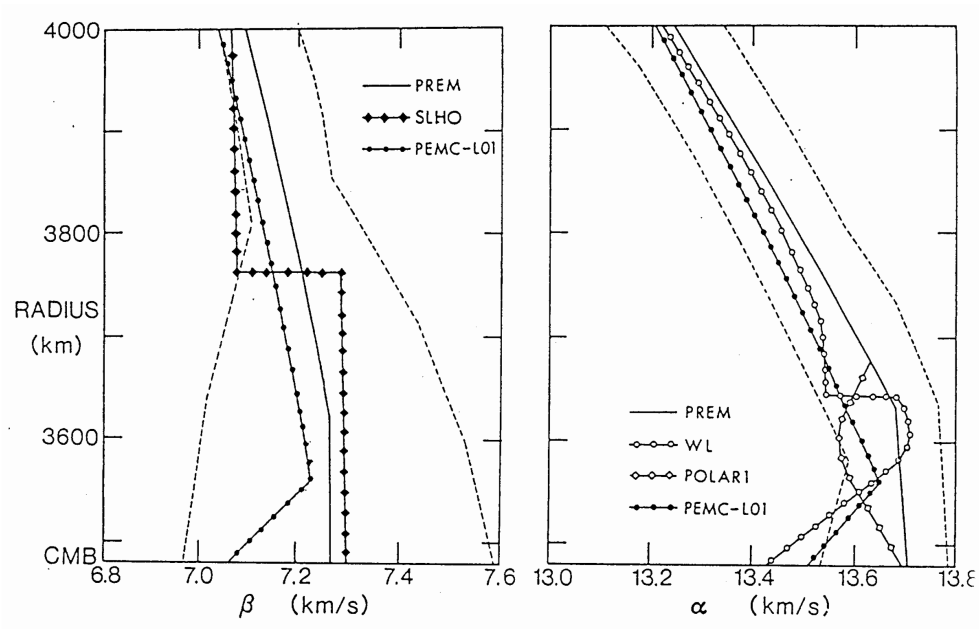



Figure 3.2.4-1: Various shear wave (left) and P wave (right) velocity models that have been proposed for the D” region at the base of the mantle. Different data were used in developing these models, and clearly there is no best average structure.

While the core-mantle boundary itself appears to quite sharp (it is an efficient reflector of high frequency seismic waves), and has little topography (probably less than a few kilometers on average), the overlying boundary layer at the base of the mantle, the D” region is very complex. The strong seismological heterogeneity observed in this region is analogous to that found in the lithosphere, where we know that strong chemical and thermal boundary layer structures with complex dynamics reside. Mineral physics experiments indicate that a strong temperature contrast exists between the core and the mantle, thus D” is likely to have a significant thermal boundary layer. There is seismological evidence for local stratification in D” [Figure 3.2.4-1] which further suggests the presence of either phase changes or chemical heterogeneity. The latter could result either from early mantle differentiation, downwelling of subduction products, or ongoing chemical reactions between the mantle and core. The combination of a hot thermal boundary layer, presumably with very low viscosity, and possible chemical heterogeneity leads to a complex image of the core-mantle transition zone [Figure 3.2.4-2]. This region serves both as the boundary condition on the core flow regime as well as the lower boundary layer of the lower mantle convective regime.

The core-mantle boundary is thus of great interest because we can associate the heterogeneity in

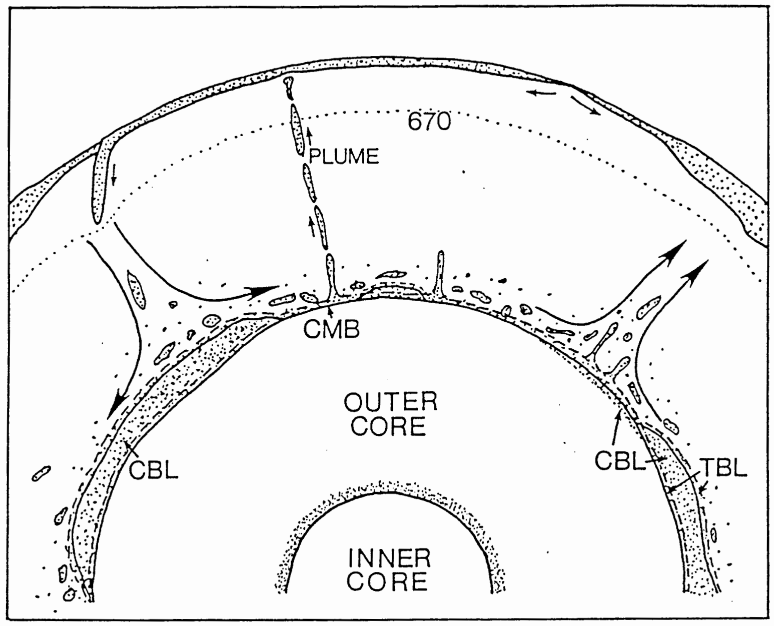



Figure 3.2.4-2: A schematic diagram for the core-mantle boundary region including the heterogeneity associated with both thermal boundary layer (TBL) and chemical boundary layer (CBL) structure. There may be some heterogeneity in the outermost core in regions of topographic highs on the CMB induced by large-scale upwellings in the mantle. Localized plumes due to thermal instabilities may also exist, some persisting to the surface of the Earth.

the region with geological dynamics, much as lithospheric heterogeneity can be related to evolution of the surface boundary layer. On the one hand, a region becomes heterogeneous in response to active processes (e.g., partial melting and differentiation; incomplete remixing; deformation), and on the other it is heterogeneities, especially in density (compositional–thermal heterogeneities), that drive global-dynamic processes.

In this sense, the core-mantle boundary holds a special interest as a uniquely active region of our planet. Indeed, some laboratory experiments support this impression by showing that liquid iron alloy (core material) reacts vigorously with crystalline silicates and oxides (lower mantle material) at the conditions of the lowermost mantle. In short, the core-mantle boundary may be be one of the more chemically active region of our planet (see 3.3.5).

The most pressing need is for more complete, detailed observations of the core-mantle boundary region by a variety of approaches, but with a definite emphasis on seismology. In particular, it is essential that we be able to correlate the results of detailed seismological investigations with observations of the geomagnetic field, its secular variations and reversal characteristics. Accomplishing this will require further theoretical work in magnetohydrodynamics and induction processes, so that the results of seismology, mineral physics, geodesy and geomagnetism can be properly integrated.

Seismological observations are required to map variations in strengths and length–scales of heterogeneities, radial thickness of the heterogeneous layer (D”) and anisotropy at the base of the mantle. Also, it is crucial that we be able to resolve whether or not heterogeneities exist in the outermost core, as has been suggested in a few recent studies.

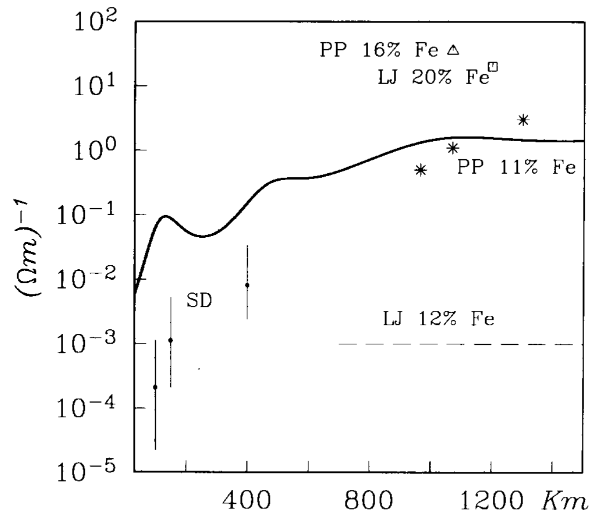



Figure 3.2.4-3: Electrical conductivity of the mantle as derived from analysis of inversion of magnetic variations and magnetic plus electrical field variations at the Earth's surface. Also shown are estimates of the conductivity of mantle materials based on laboratory measurements. (SD: olivine; PP: perovskite plus magnesiowüstite; LJ: perovskite plus magnesiowüstite; the iron contents are indicated)

At the same time, further experimental work is required in mineral physics and petrology. Temperatures and the approach to chemical equilibrium in ultrahigh- pressure experiments need to be quantified more reliably. Doing so will give us detailed information on the temperature distribution at the base of the mantle, as well as on the ways in which the core-mantle system has evolved geochemically over the age of the Earth.

Because the lower mantle comprises the bulk of the Earth, its electrical conductivity is a property of great interest for propagation of core geomagnetic disturbances and possible core-mantle coupling, as well as problems of bulk composition, mineralogy, and temperature. Figure 3.2.4-3 shows a recent electrical conductivity profile that is based upon inversion of magnetic variations (Geomagnetic Deep Sounding) and magnetic plus electrical field variations at the Earth's surface (Magnetotellurics). The latter method is less affected by our incomplete knowledge of the ionospheric source fields and provides better depth resolution. The inversion process has been forced to produce a smooth curve.

Although electromagnetic inversions can vary substantially, there is commonly a high conductivity layer at about the depth of the upper mantle seismic low velocity zone, sometimes a jump near the 400 km discontinuity, and another rise close to the 670 km discontinuity. It is supposed (but not established) that the phase transitions at 400 and 670 km cause the jumps at these depths while a number of hypotheses have been advanced to explain the upper mantle high conductivity layer. These include partial melting, intergranular carbon, and traces of hydrogen inside olivine or pyroxene crystal structures. This unique sensitivity to these trace materials that gives electrical conductivity a special view of the Earth's interior.

### 3.2.5 The Earth's Core

The outer core is a vast magma chamber inside the Earth, filled with molten metallic alloy in a layer 2260 km thick between the crystallinelower mantle and the inner core. The fact that the outer core is liquid, with no or very little elastic rigidity and a viscosity close to that of water, has been well established by seismological and radio astronomical observations. Seismic shear waves cannot propagate through the outer core, and one of the characteristic 'fingerprints' of the Earth is the difference in the compressional and shear wavefields. Both body wave and free oscillation measurements, as well as frequencies of the forced nutations bound the outer core rigidity to a very small value. Free oscillations require that the inner core be solid, as some energy propagates there in the shear mode, and this is compatible with the behavior of body wave reflections off of the inner core boundary. The inner core may be partially molten, particularly near its surface, but the inner core-outer core boundary is quite sharp.

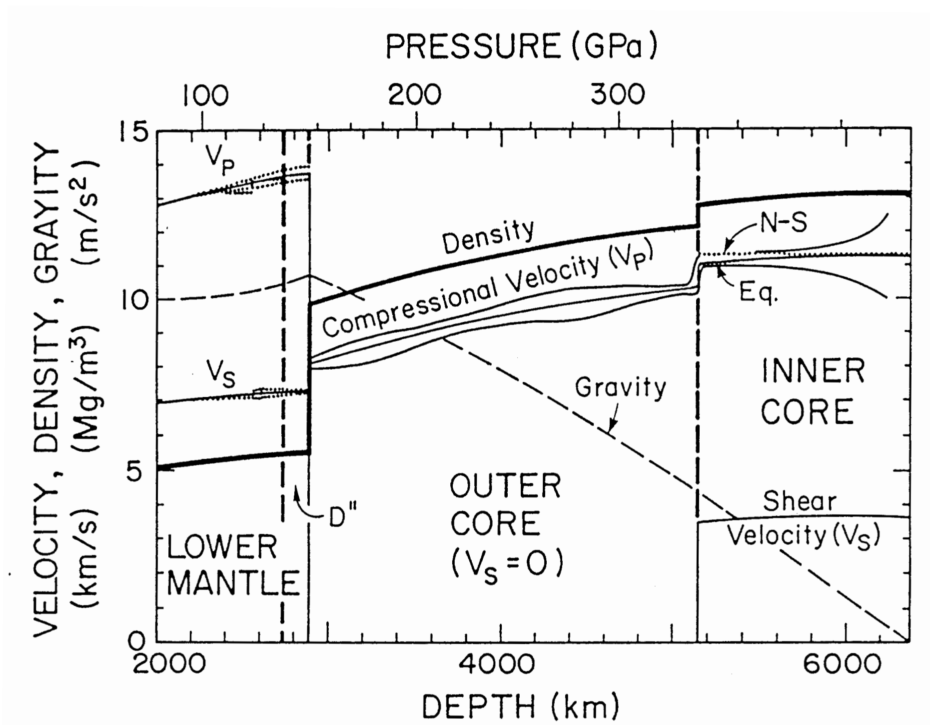
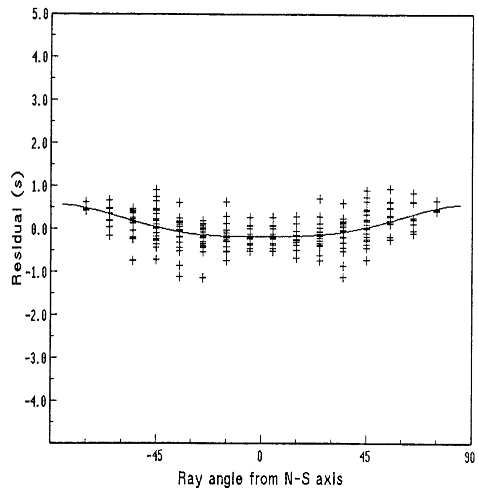



Figure 3.2.5-1: Seismologically measured density, elastic wave velocities, and gravitational acceleration through the core and lowermost mantle are shown as functions of depth and corresponding pressure. Extremal bounds on the average P velocity at each depth are included. The difference between the polar and equatorial compressional velocities in the inner core is also indicated.

Seismic waves that penetrate into the core have relatively little scatter in travel time compared to waves in the mantle, indicating that lateral heterogeneity is rather weak. Using a combination of seismic phases the density and elastic velocity structure of the core have been well-determined [Figure 3.2.5-1]. There is some evidence for the outermost 20-100 km of the core to be anomalous with respect to the deeper regions, with slightly reduced velocity gradients, and possibly lateral variations. This may be the manifestation of a core-side thermal or chemical boundary layer. There is also recent evidence for a reduction of the velocity gradient just above the inner core, again a possible boundary layer effect near the intersection with the liquidus of the core forming alloy.



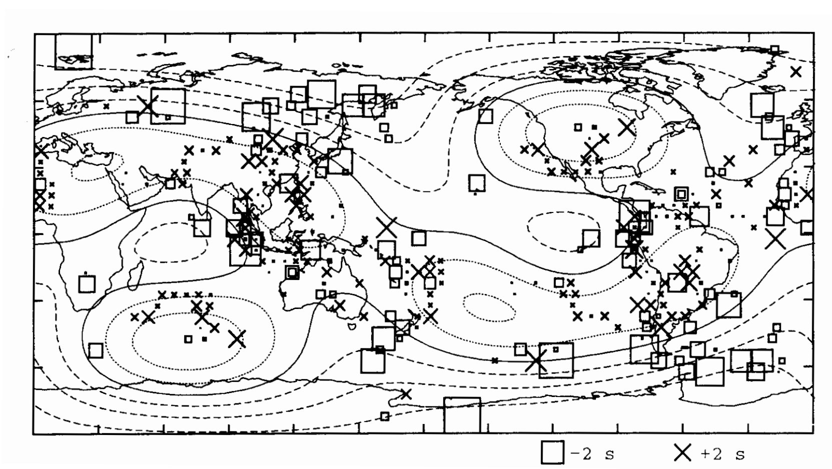




Figure 3.2.5-2: Two separate analyses of PKIKP travel times anomalies, revealing a pattern of more negative anomalies (faster velocities) for paths through the inner core along the polar direction. The top plot shows the residuals as a function of azimuth from the axis. The lower plot is a map of the anomalies at the source and receiver locations, with a low order, degree 4, expansion of the pattern.

The bulk composition of the core is believed to be nearly pure iron based on several lines of evidence. First, the internal geomagnetic field must be produced by a dynamo mechanism, which requires the existence of a conductive fluid region inside the planet, and the outer core is the only plausible region. Second, the observed density and acoustic velocity of the core are compatible with those of iron measured at corresponding pressures and temperatures, if allowance is made for a 10% light alloying component. And third, the cosmochemical abundance of iron makes it the primary abundant element compatible with the observed properties of the core. The inner core-outer core boundary is viewed as the intersection of the core geotherm with the effective melting temperature of the core alloy.

The inner core has elastic properties that are close to those of pure iron–nickel alloy, so the progressive growth of the inner core brought about by cooling of the planet is leading to progressive enrichment of the light alloy component of the outer core. This is a probable source of energy feeding the convective motions in the core producing the geodynamo. Seismologists have detected evidence of directional-dependence of seismic velocity for waves traversing the inner core. Paths traveling along the rotational axis travel faster through the core than waves in the equatorial plane [Figure 3.2.5-2]. This may be the result of anisotropy induced by convection within the inner core. Estimates of the Rayleigh number for the inner core are about 6 orders of magnitude larger than the critical Rayleigh number for an internally heated sphere. The predominant mineral phase of the inner core is hcp iron, which is believe to have anisotropic properties.

However, it is also possible that the directional dependence of seismic velocity through the core actually arises from outer core structure. If there is axial symmetry to the outer core, induced by the dynamic regime, it may be that weak outer core heterogeneity may exist in the 'cap' above and below the inner core along the rotational axis. These regions may be dynamically isolated to a large extent from the overall core flow regime, and thus may have slightly different thermal and chemical structure due to the proximity of the geotherm to the core solidus. A variation in suspended particulates or light alloying component could affect the average seismic velocities. This is a major research problem to be tackled, which requires close interaction between seismologists, mineral physicists and geodynamicists.

Other fundamental issues associated with the core structure involve identifying the light alloying component. It is likely that this includes more than one alloying constituent, with likely candidates being O, S, Ni, and H. Ascertaining whether any radiogenic components partitioned into the core is also of importance for assessing the energy budget available to drive the dynamo. Since oxygen and sulfur are among the most likely alloy constituents extensive experimental work has been undertaken on the melting relations in the Fe-S and Fe-O systems. These systems have very different high pressure behavior, and some controversy in the experimental results, which results in significant uncertainty in the actual temperature structure in the core. Values for the temperature at the core-mantle boundary range from 3000°C to 6000°C, and clearly the uncertainty needs to be reduced if we are to understand the dynamic regimes in both the mantle and the core.

## 3.3 THE DYNAMICS AND EVOLUTION OF THE CORE

The innermost region of the Earth is the core. No direct measurements can be made of any of its physical properties and in many ways we know more about stars than about this portion of our own planet. The existence of a liquid core is inferred from the behavior of seismic waves and by the existence of the geomagnetic field. Its size is found from seismic data, and confirmed by the characteristics of the temporal change of the geomagnetic field. Its radius is just over half that of the Earth and it is divided into a fluid outer core and a solid, possibly mushy, inner core. But the core is not static. The fluid there is in motion, providing the geodynamo; the inner core is growing as outer core fluid freezes at its boundary. And the dynamics of its motion are complicated by not only Coriolis forces but, because its fluid is a conductor moving in a magnetic field, also by Lorentz forces. Information regarding the dynamics of the core comes from the temporal variation of the geomagnetic field and from analyses of characteristics of the Earth's rotation.

### 3.3.1 History of the magnetic field and reversals

The most precise picture of the Earth's magnetic field and its secular variation comes from ancient mariners' data, magnetic observatory data, and satellite data. The former is available for the past 350 years, the observatory data for the past 150 years, and the satellite data for the past two decades. These data show that the present field at the Earth's surface can be well-described by a geocentric axial dipole tilted 11o with respect to the spin axis. Approximately 20% of the field at the Earth's surface cannot be fit by this dipole field and this is referred to as the non-dipole field. The dipole field is decreasing in intensity at about 5% per century and on the average the non-dipole field is drifting westward at about 0.18 deg/yr. However, the variation in the non-dipole field is complex; westward drift is largely confined to the Atlantic hemisphere and there are some locations where the drift is even eastward. The magnetic field can be downwardly continued to the core–mantle boundary, as discussed in section 3.3.2 where it can be used to provide estimates of the core's velocity field, as discussed in section 3.3.3.

The Earth's magnetic field has existed for more than 2.5–3.5 billion years, $10^7$ times longer than the historical record, and therefore one must turn to paleomagnetism to obtain many of the properties of the field and its evolution. The most dramatic property of the field is that it reverses polarity. The time for the transition between normal polarity (state of the present field) and reverse polarity is approximately 4000 years, although some estimates are as short as 1000 years, and some exceed 10,000 years. One current controversy concerns whether the field is predominantly dipolar (at the Earth's surface) or non-dipolar during a transition. Another is whether there are preferred geographic paths that the pole follows during transitions. Still another is whether transitions occur more or less continuously or with rapid changes separated by times with little change.

The magnetic field is in a transitional configuration about 0.5% of the time. The intervals separating reversals vary considerably in length; the reversal chronology appears to reflect a stochastic process, but not a stationary one. This is reflected in the rate of reversals versus time as shown in Figure 3.3.1-1. Note there were no, or very few, reversals for an interval of nearly 35 million years when the field exhibited normal polarity during the Mesozoic Era. Less well-documented is a roughly 50 million year interval of constant reverse polarity that occurred during the late Paleozoic Era. Such changes as shown in Figure 3.3.1-1, probably reflect changes in the core-mantle boundary conditions, as discussed further in section 3.3.5. At present the dipole portion of the field is decreasing in magnitude at a rate that, if continued, will result in disappearance of the dipole field in about 1200 years. This rate is 5 - 10 times the rate of free decay of the field. It is possible we are experiencing the onset of a reversal.

In principle, secular variation from lake and rapidly deposited marine sediments should provide valuable input on whether changes seen at present and in the historical record are typical; to date these data are inconclusive. It is also desirable to obtain paleosecular variation from magnetostratigraphic sections in older rocks to make comparisons with more recent records of secular variation.

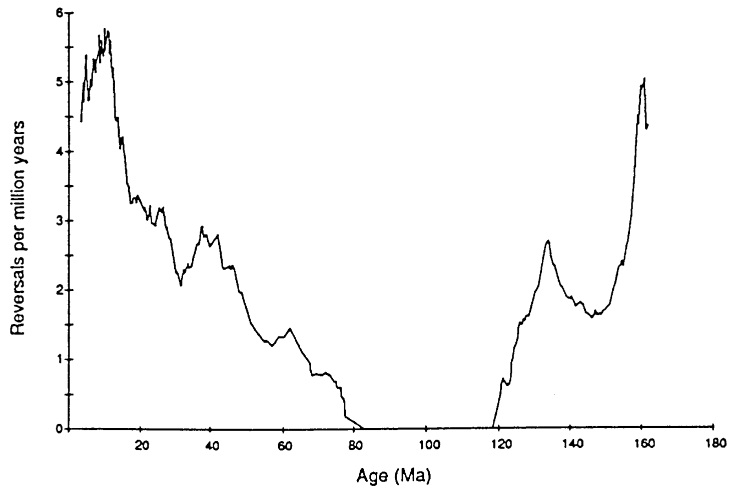



Figure 3.3.1-1: Estimated mean reversal rate from the present back to 165 Ma.

The paleomagnetic results discussed above depend only on measurement of the field direction impressed upon the rocks, not field intensity. Paleointensity data from archaeological artifacts and lava flows indicate that the intensity has varied during the last 10,000 years by 140% about the present intensity. There are serious rock magnetic problems associated with obtaining reliable intensities in older rocks. However, preliminary data suggest that the average intensity of the field is similar to today's except possibly from 175 Ma to 110 Ma when the intensity appears to have been lower. Note that this interval of low intensity is apparently different from that in which reversals were absent. There are virtually no reliable paleointensity data for rocks with ages more than a few hundred million years.

Excluding reversals, the magnetic field at the Earth's surface averaged over thousands of years appears to be that of a geocentric axial dipole field with minor contributions from axial non-dipole components. Surprisingly, the time averaged reverse and normal polarity states appear to be slightly, but significantly, different; this seems to suggest that other processes, perhaps in the lower mantle may affect the main field. More data are required to confirm this polarity asymmetry and to determine how the time averaged magnetic field has varied over long time intervals (tens to hundreds of millions of years).

Paleomagnetic data provide the only source of information about the magnetic field prior to a few hundred years ago. Substantially more data are needed to extend and improve our knowledge of the reversal chronology and the process by which the field reverses and to determine how typical the present field is. Reliable paleointensity data are needed for all ages. Finally, rock magnetic studies are needed to allow one to distinguish artifacts in the magnetic recording system from signals reflecting the properties of the magnetic field in the past.

### 3.3.2 The magnetic field at the core-mantle boundary

Maps of the magnetic field at the core-mantle boundary (CMB) are one of the few probes that we have to infer the dynamics of the Earth's fluid outer core. The variations of the field over time scales from years to centuries; periods over which we have direct observations of the field, result primarily from the advection of field lines by fluid flow near the surface of the core. Maps of the field at the CMB not only provide a starting point for determinations of the pattern of fluid flow at the core surface, patterns which are of great use in a host of geophysical investigations of the dynamics of the Earth's deep interior, but also provide valuable insight into the dynamo process that maintains the magnetic field against ohmic decay.

The last decade has seen increased interest in mapping the magnetic field at the CMB as the result of several advances in a broad range of different subject areas. Foremost among these has been the availability of high quality satellite data: here, as in other areas of geophysics, new data are the primary catalyst for new advances. But other factors include: advances in computing technology enabling more complete models of the magnetic field to be constructed and stimulating fresh interest in computational dynamo theory; advances in inverse theory that have led to a more complete understanding of the problems involved in mapping the field at the CMB; and advances in mineral physics and seismology that have provided new constraints on the hydrostatic equilibrium of the core. Some of the resulting models are shown in Figure 3.3.2-1.

What is needed in order to take fuller advantage of these data, and to integrate these studies with theoretical and computational investigations of the geodynamo? The maps of the magnetic field at the CMB produced until very recently are based on a very restrictive set of assumptions: the effects of the external field, the crustal field, and the electrical conductivity of the mantle are basically ignored, or dealt with by extreme simplifying assumptions. The latest generation of maps have begun to take account of the external field and the crustal field, but mantle conductivity is still largely neglected. The crustal field is particularly pernicious since it masks the core field at high spherical harmonic degree (say above degree 13) from our view; accordingly maps of the field such as those shown in Figure 3.3.2-1 are limited to degree less than 13. This could be of considerable consequence since by some estimates it omits half or more of the poloidal field at the CMB. A considerable effort, drawing in particular on crustal modelling, is needed if we are to develop methods of seeing through this filter.

To incorporate the effects of mantle conductivity also requires an interdisciplinary approach: mineral physics and electromagnetic induction studies can jointly place constraints on the radial conductivity structure; seismic tomography and mineral physics can address the exciting, but theoretically challenging, possibility of lateral variations in, and even anisotropic, conductivity structure in the lowermost mantle.

Although invisible to us at the Earth's surface, dynamo action in the core demands not only the poloidal field we have been discussing but also a toroidal field. Toroidal fields are generated from poloidal fields in the core via the action of differential rotation. One suggestion is that this process reaches its limit when the Lorentz force balances the Coriolis forces on the convective motions. In this case the toroidal field could easily exceed $10^{-3}$ Tesla (T). If the Coriolis forces are balanced by the fluid pressure then the toroidal field could be much smaller. The poloidal field at the CMB has a strength of about $10^{-5}$ T. Because toroidal fields require meridional currents, they are unobservable at the surface of the Earth; what may be the largest portion of the magnetic field of our planet is

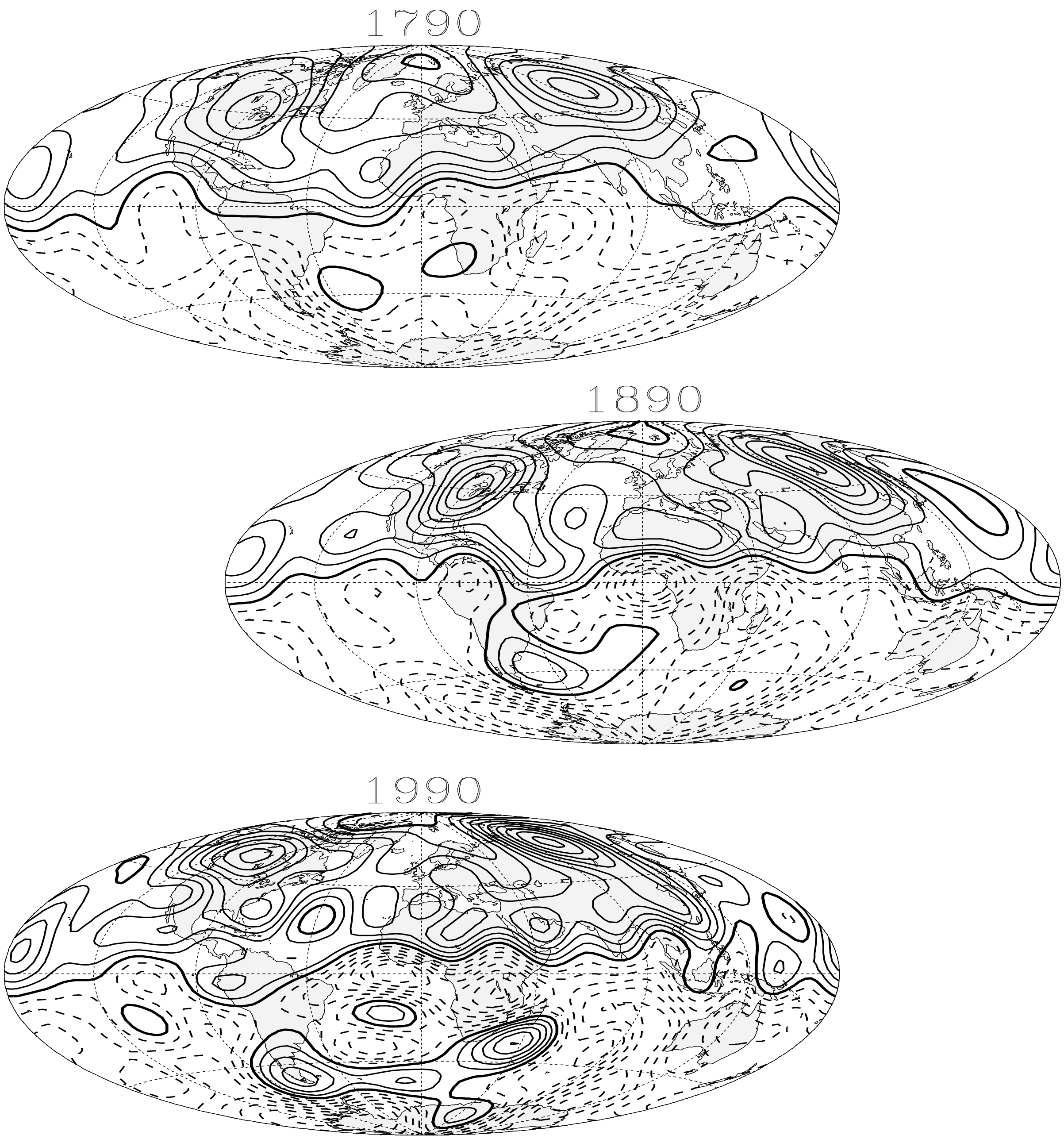



Figure 3.3.2-1: Maps of the radial component of the magnetic field at the core-mantle boundary at 100 year intervals (1790, 1890 and 1990). The solid lines are negative contours, the broken lines positive contours, and the bold lines zero contours. The contour interval is 100mT. The map projection is Aitoff equal-area.

invisible to us and must be inferred from theories of the dynamo.

In spite of difficulties and shortcomings, the maps of the poloidal field at the CMB that we already have are of substantial interest. For example, they show that at the CMB non-dipolar ingredients of the field contribute substantially, although the underlying dipole is still evident in the approximate zonal pattern of field contours. Further, the maps for different times reveals patches of field which drift westward while others remain stationary. Also, evidence of magnetic diffusion is present for some regions.

To integrate these studies with geodynamo theory will require an extensive collaboration between observers on the one hand, and theoreticians on the other. The challenge is to bring these groups together so that questions can be posed that both groups can address. Only then can real progress on the dynamo problem, one of the outstanding unsolved problems in physics be expected.

### 3.3.3 Fluid flow in the outer core

A major use of maps of the magnetic field at the CMB is to determine the pattern of fluid flow at the surface of the fluid outer core (*cf.* Figure 3.1.1-4), which in turn enables a wide range of investigations of the dynamics of the Earth's deep interior. A constraint in this procedure, which discouraged researchers for some time, is that unless other assumptions about the velocity of the fluid than inductional motion are made, the computed fluid flow patterns are non-unique. Recently, however, it was realized that often those assumptions are exactly the sort of hypotheses about the fluid flow which should be tested,*e.g.*, whether or not the flow is steady for some period of time, or geostrophic, or subject to some other constraint.

A primary motivation for determining the fluid flow at the core surface is to provide additional insight into the dynamo. Is the flow at the core surface geostrophic, resulting from a balance between the Coriolis force and pressure gradients, or does the magnetic field directly affect the dynamics of the flow through the Lorentz force? Is the flow consistent with a stably stratified density profile at the core surface, as might be expected from some models of the core, or does convection penetrate to the core surface? What is the radial length scale of convection in the core, especially near the core surface, in other words, is the pattern of fluid flow near the core surface indicative of the pattern of flow throughout the core (whole-core convection), or is the flow at depth markedly different (layered core convection)?

The pattern of fluid flow at the core surface is also an essential tool for understanding core-mantle interactions, including interactions that result directly in a transfer of angular momentum between the core and mantle (which are manifested as variations in the Earth's rotation) and interactions that do not exchange angular momentum, such as thermal interactions, which are nonetheless an important ingredient of the dynamics of the deep interior. Understanding these interactions will only be possible through collaboration with other disciplines within deep Earth geophysics. For example, thermal interactions can only be understood through the combination of models of the fluid flow, seismic images of lowermost mantle, and convection studies of coupled systems. Understanding pressure coupling at the CMB requires not only the flow at the core surface, but also the topography of the boundary, obtained from seismology and geodynamics. Electromagnetic coupling requires the electrical conductivity structure of the mantle. And both of these coupling mechanisms require geodetic observations to assess the resultant torques in terms of variations in the Earth's rotation.[Figure 3.3.3-1]

An important future step in core dynamics is to relate the patterns of core flow inferred from the secular variation of the magnetic field to the patterns of core motion predicted from models of convection The structure of convection in a rotating spherical shell in the laboratory and that from a three–dimensional numerical simulation are shown in Figure 3.3.3-2. The addition of the Lorenz force due to the magnetic filed will make it possible to use both laboratory and numerical models as tools for interpreting core flow patterns in terms of dynamical processes.

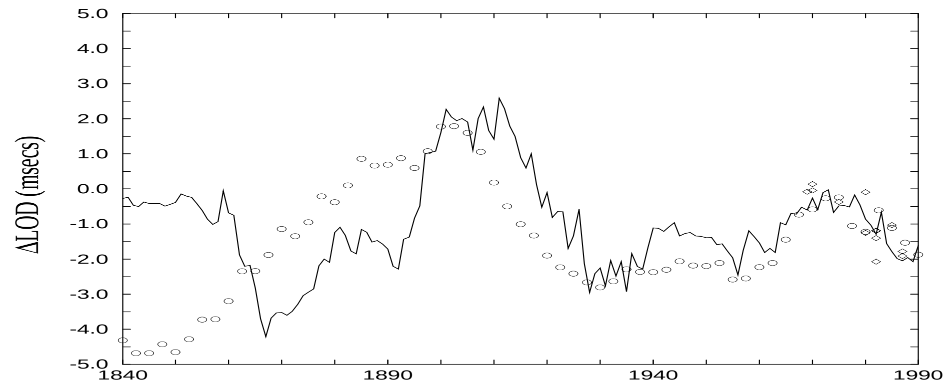



Figure 3.3.3-1: Observed excess length of day (LOD) from geodetic observations (solid line) compared with the predicted values calculated from models of core flow based on geomagnetic observations (circles).

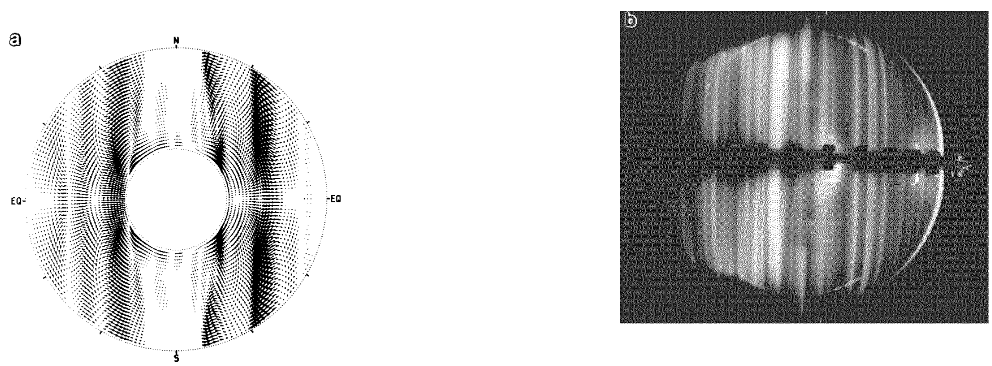



Figure 3.3.3-2: Meridional sections of rotating spherical convection from (a) numerical calculations, and (b) laboratory experiments. This columnar style of convection has been proposed as an explanation for some aspects of the core motions inferred from geomagnetic secular variation.

All these fields have undergone major advances in the last five years. Taken separately, these advances appear to only highlight the complexity and richness of the dynamics of the CMB region. The challenge now is to bring them together, by assembling the individual scientists and research groups involved, to form a new model of this inaccessible region of the interior.

### 3.3.4 Generation of the geomagnetic field

The origin of the magnetic field of the Earth is a fundamental problem of geophysics. Although a number of other mechanisms have been proposed, the dynamo theory is the only one that is capable of explaining several important features of the field: the near alignment of its dipole axis with the rotational axis of the Earth, the surprisingly rapid secular variation of the non-dipole field observed at the surface of the Earth and the irregularly timed reversals of the polarity of the field over geological time. According to this theory, the geomagnetic field is maintained against ohmic losses by the dynamo action of convective motions within the liquid outer core. The geomagnetic dynamo problem is an exceedingly difficult mathematical challenge and attempts at analytic solution have been only partially successful; the solutions obtained so far are valid for idealized geometries and conditions which allow no more than hints at the behavior of the actual geomagnetic field.

It is widely agreed that the Earth's dynamo is powered by compositional convection associated with solidification of the inner core engendered by the slow cooling of the Earth over geologic time, and that the dominant force balance in the core is magnetostrophic (e. g., a balance between Coriolis, Lorentz and pressure forces). This is sometimes referred to as the strong-field regime; the weak-field regime being essentially geostrophic. However, there are grave uncertainties concerning the detailed mechanisms operating. For example, it is not known whether the dynamo is of alpha–squared or alpha–omega type, or whether it is 'nearly axisymmetric' or 'model-z' type. Until these uncertainties are fully resolved, the problem of understanding the Earth's magnetic field cannot be regarded as settled.

A successful dynamo model must be capable of explaining the cause of reversals and secular variations, and provide at least a statistical prediction of the rate of reversals and the character of secular variations. Important paleomagnetic and geomagnetic observational data which feed in to this problem thus include the reversal-frequency record, the typical structure of the field during reversals and the present-day secular variations. The secular-variation data is of particular importance because it can be inverted to obtain information concerning the pattern of fluid motions at the top of the core (see 3.3.2 and 3.3.3).

Until recently, dynamo theory developed as a relatively isolated discipline within geophysics. However that situation is beginning to change as our ideas of the interplay between the core and the rest of the Earth have matured. For example, the power supply to the dynamo is intimately coupled to the thermal and dynamical state of the lowermost mantle. The heat cast off by the core is believed to be carried to the surface by mantle plumes, which are recognized to play an important role in surface processes such as plate reorganization and the formation of flood basalts and island chains. A realistic model of the long-term behavior of the dynamo will have to be coupled to the dynamical and thermal state of the mantle, as determined by seismology, mineral physics and theories of mantle dynamics. In addition, a realistic model of the dynamo will require the use of reliable estimates of the important parameters such as thermal and electrical conductivity of the lowermost mantle and the core. Such estimates are just beginning to be produced by high-pressure laboratories.

The dynamo problem is three-dimensional and time-dependent. Consequently, although analysis will continue to play an important part, it is generally accepted that the ultimate solution of this problem will be computational in nature. The development of a numerical code which provides a reliable and realistic model of the Earth's magnetic field is a formidable task that will require a sustained cooperative effort as described in section 4.

Solution of the problem of the origin of the Earth's magnetic field will involve an interplay between theory, numerical computation, models of the mantle, observations of the geomagnetic field and data concerning the properties of materials at high pressure and high temperature. Such a solution can be obtained only through the cooperative efforts of geoscientists from a number of areas of geophysics. Progress toward this goal will be greatly facilitated by the implementation of the science plan described in below.

### 3.3.5 The core's thermal-chemical evolution and interaction with the mantle

The Earth's core is believed to have formed within the first few hundred million years after the Earth was formed 4.6 billion years ago. This belief is consistent with paleomagnetic data that indicate the magnetic field has a minimum age of 3 billion years. To satisfy seismic and shock wave data about 10% (by weight) of less dense elements are also required; the prime candidates for these elements are oxygen, sulfur and hydrogen. Although the temperatures in the core remain somewhat uncertain due to uncertainties in the estimates for the melting of iron and in the core's composition, the temperature at the CMB is probably near 4000°K. Using this value, the temperatures anywhere else in the core can be obtained providing one can obtain an accurate estimate of the adiabatic temperature gradient. However, recent estimates of this gradient in the core range from 0.7°K/km to 1.2°K/km. This variation is one example of the present uncertainties in mineral physics parameters that can have a strong impact on models for the Earth's thermal properties and history.

The heat transferred down the adiabatic gradient and out of the core is around $4 \cdot 10^{12}$ W, i.e. approximately 10% of the heat flow at the Earth's surface. This heat contributes nothing to the power available to drive the geodynamo. Thermal convection may power the geodynamo, but if so, it must be due to heat that is in excess to that transported down the adiabat.

As the Earth cooled it formed a solid inner core with nearly pure iron composition. (This 'solid' inner core may also be convecting on a much longer time scale, as is suggested by recent seismic anisotropy measurements.) Compositional buoyancy associated with the freezing of pure iron and the release of less dense elements occurs near the inner- outer core boundary. Estimates of the buoyancy resulting from this incongruent freezing at the inner core boundary appears comparable to the thermal buoyancy at the CMB. However, energy associated with compositional convection is presently preferred over thermal convection for powering the geodynamo because of efficiency considerations. Nevertheless, this could not always have been the case, since the amount of compositional buoyancy has been increasing over geological time as the volume of the inner core has increased. The time of formation and rate of growth of the inner core is model dependent and will remain poorly constrained until accurate estimates of certain critical parameters from mineral physics are forthcoming. One expects that paleomagnetic data, particularly paleointensity data, should provide valuable information on the inner core growth, but at present the measurements are too few and the rock magnetic problems too many for reliable conclusions to be drawn.

The properties and evolution of the CMB are also poorly known but for different reasons. The CMB can be considered as the major discontinuity in the Earth with a density contrast of 4.4 g/cm$^3$ between the liquid metallic core and the solid Mg–Fe–Si–O (perovskite and magnesiowüstite) mantle. A roughly 200 km thick layer at the base of the mantle, the D" layer is believed to be a thermal boundary layer in which a chemical boundary layer is embedded (section 3.2.4). Its seismic properties are known to vary laterally, although the scales and magnitudes of these variations are as yet poorly defined. The bottom of this layer, i.e., the CMB, probably exhibits topography; the amplitude estimates of this topography vary from a few hundreds of meters to a few kilometers.

In addition, it seems likely that the core is not in chemical equilibrium with the mantle and therefore, the CMB is chemically active. Recent mineral physics experiments suggest that there may be regions of metallization near the base of D" [Figure 3.3.5-1]. Establishing the lateral variations in D" is important for interpreting a variety of geophysical data. For example, both topography, through viscous coupling, and metallic regions with enhanced electrical conductivity, through electromagnetic coupling, can affect variations in the length of the day. Because of the

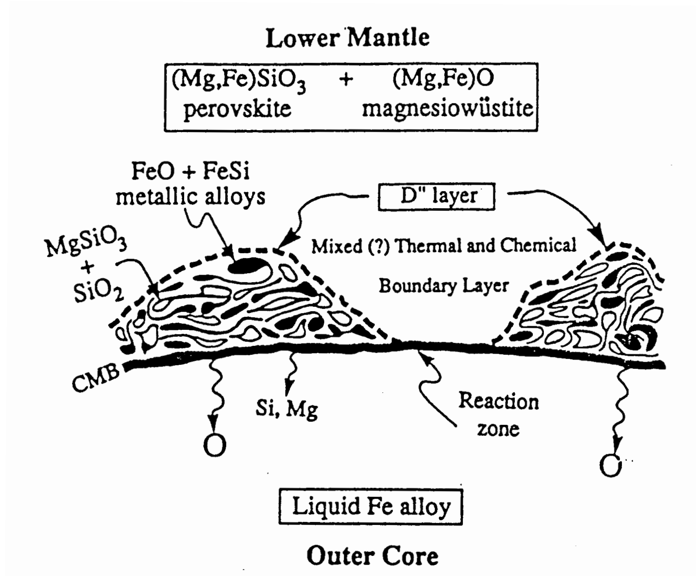



Figure 3.3.5-1: Structure of the core-mantle boundary (CMB) and D" region, as suggested by geophysical and experimental observations. A reaction zone 10–100 m thick is created at the interface between the mantle and core. Mantle components (O and lesser amounts of Si and Mg) are dissolved into the outer core and rapidly dispersed by the turbulent flow of the liquid iron alloy. On time scales greater than 10Ma the reaction zone at the CMB is entrained by the large-scale convective flow of the mantle, but cannot be raised upward more than a few hundred km because of the high density of the reaction products relative to the mantle. The resulting mixture of unreacted mantle and of heterogeneous reaction products makes up the D" layer.

large density contrast, topography in the CMB also affects the Earth's gravitational field (i.e. the geoid). Both CMB topography and regions of enhanced electrical conductivity in the lower mantle can affect the Earth's dynamo.

The CMB also appears to have evolved over hundreds of millions of years. This is reflected in magnetic field reversal data, such as shown in Figure 3.3.1-1 and in paleosecular variation data. Slow changes at the CMB would be primarily controlled by processes in the mantle. It remains uncertain whether these magnetic field changes reflect small changes in the mean temperature of the CMB or some other property such as changes in the CMB topography with time.

The above discussion illustrates the large gaps in our knowledge of the thermal- chemical evolution of the Earth's deep interior and that a strong interdisciplinary approach is required to solve many of the outstanding problems: mineral physics to provide critical parameters for thermal and chemical evolution; seismology to define better the present state of the core and D", including its topography; paleomagnetic data to provide information on the evolution of the core and D";. gravity and earth rotation data to provide information on the distribution of density near the CMB. Finally, theoreticians need to consider all of the above to obtain improved models for the thermal and chemical evolution of the Earth's deep interior.

## 3.4 DYNAMICS AND EVOLUTION OF THE MANTLE

There has been substantial progress in moving from the kinematic model of plate tectonics to a new perspective of a global three-dimensional dynamic Earth system, but great challenges lie ahead. These are at the frontiers of all of the deep Earth disciplines, and particularly in the fostering of new interdisciplinary insights.

### 3.4.1 Numerical simulations of mantle convection

A number of factors make mantle convection a more complicated and richer phenomenon than can readily be addressed by physical experiments in laboratory tanks alone. These include the effects of three-dimensional spherical geometry, compressibility, compositional variations, phase transitions, and a rheology that depends on temperature, pressure, and stress in a complicated way. Recently, computer hardware and software has advanced to the point where these phenomena can now be studied (albeit not all at the same time) via numerical experiments. Sophisticated codes are now exploiting both vector and parallel architecture machines. For two-dimensional calculations, well–resolved numerical simulations at high Rayleigh number, including all but the first of these complications, are now tractable; the effects of three-dimensions, including sphericity, can also be explored, although for simpler physics and at lower Rayleigh number.

One important factor governing mantle convection is that the existence of rigid plate interiors separated by weak plate boundaries has a profound influence on the system (see also section 3.4.3). Geodynamicists are now beginning to explore the effects that variable plate geometry has on the thermal structure and evolution of the mantle. For example, Figure 3.4.1-1 shows a sequence of temperature fields for a convection simulation that starts with a plate of dimensionless width 3 at the surface. The boundary conditions are periodic, such that flow out of one side of the box ”wraps around” to return into the other side. The plate is fractured by a hot upwelling, with the two fragments eventually colliding over a cold downwelling. The temperature field has much more long-wavelength heterogeneity than occurs for simulations that do not include the effects of plates. The history of plate breakup and coalescence that results from this simulation has many features in common with the Wilson cycle for the opening and closing of oceans.

While most effort up to now has gone into investigation of convection driven by temperature variations alone, on Earth, heat transport and chemical differentiation are intimately linked through the process of volcanism. Over 75% of global heat transport and volcanism are the direct results of plate motion and seafloor spreading. Melting of the mantle and formation of oceanic crust at spreading centers results in compositionally induced variations in density that are much larger than those associated through thermal expansivity with temperature variations. The effects of these compositional variations on mantle convection are now being explored. For example, Figure 3.4.1-2 shows the results of a flow model that includes not only thermal and compositional effects on buoyancy, but also includes the percolation of magma through the ”solid” matrix beneath a spreading ridge. The flow is focused beneath the axial region, primarily by the compositional buoyancy that results because the dense minerals melt preferentially, leaving a residuum that is less dense than the fertile mantle. This focusing of the flow can explain a long-standing puzzle in geodynamics—that the zone of crustal formation beneath midocean ridges is much narrower than the zone of upwelling and melting that would exist if flow were the passive response to pulling apart of the plates. (Another example of a convection calculation including compositional effects, this time for a subduction zone, is shown in Figure 3.4.5-3, discussed later.)

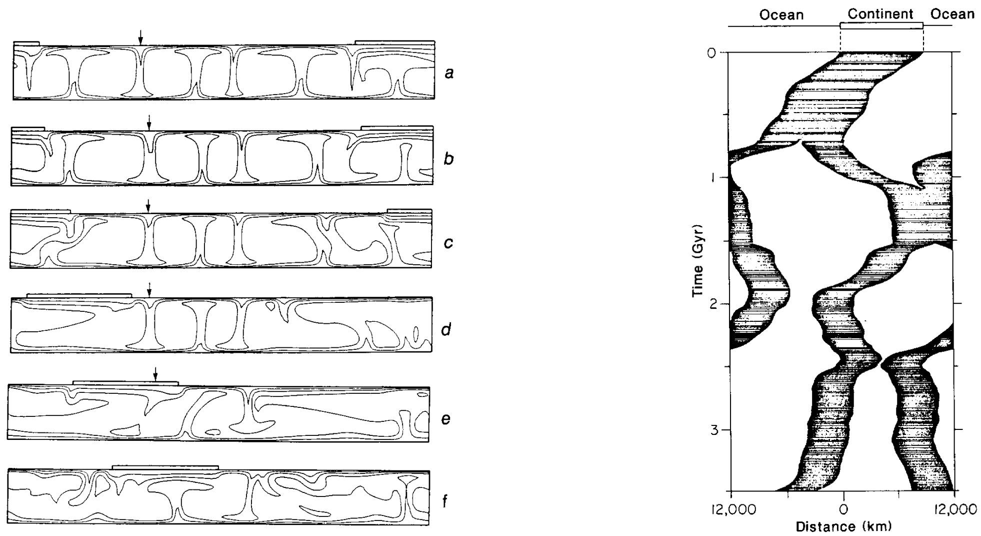



Figure 3.4.1-1: (left) A sequence of temperature fields for a convection simulation that includes a rigid plate at the surface. The boundary conditions are periodic. The sequence starts with a plate of dimensionless width 3. The plate is fractured by a hot upwelling, with the two fragments dispersing, then eventually colliding over a cold downwelling. (right) The history of plate breakup and coalescence as a function of time. Continental plates are shown in black.

Another effect of this sort comes from mineralogic phase transitions in the transition zone. Temperature changes can result in a change of the mineral assemblage present in equilibrium at a given pressure; the density change from this can be many times larger than the intrinsic density changes in individual minerals. This effect has been considered in models of subducting lithospheric slabs, where the elevation of the 450 km boundary in the cold slab has a large effect on the net density of the slab. Similarly, the 670 km phase transition may have the opposite effect, and resist the sinking of the cold slab because of the negative Clapeyron slope of this transition. These effects, which are clearly of possible major importance, have begun to be investigated in convection models.

Figure 3.4.1-3 shows the convection pattern in a two dimensional box with phase transitions separating the upper and lower halves. The figures show that the system initially convects as two separate layers, and then as time progresses the layered convection pattern breaks down and the system convects as a single layer. The implications of this for the Earth are profound, especially considering the longstanding problem of whether or not convection penetrates the 670 km discontinuity.

While three-dimensional simulations are not yet able to incorporate the complexities just discussed, important progress has been made in understanding the effects of 3-D geometry on convecting systems. For example, Figure 3.4.1-4 illustrates the fundamental asymmetry between upwelling and downwelling flows that occurs in spherical geometry. The upwellings are localized (plume-like), while the downwellings are linear (slab-like). The geodynamical observation that on Earth, both ridges and subduction zones are linear features indicates that there is physics not yet included in these simulations, possibly the effects of plates, that is important for Earth.

Some 3-D calculations in smaller domains with Cartesian geometry have begun to address one of the most important problems in geodynamics — the generation of the observed toroidal sur-

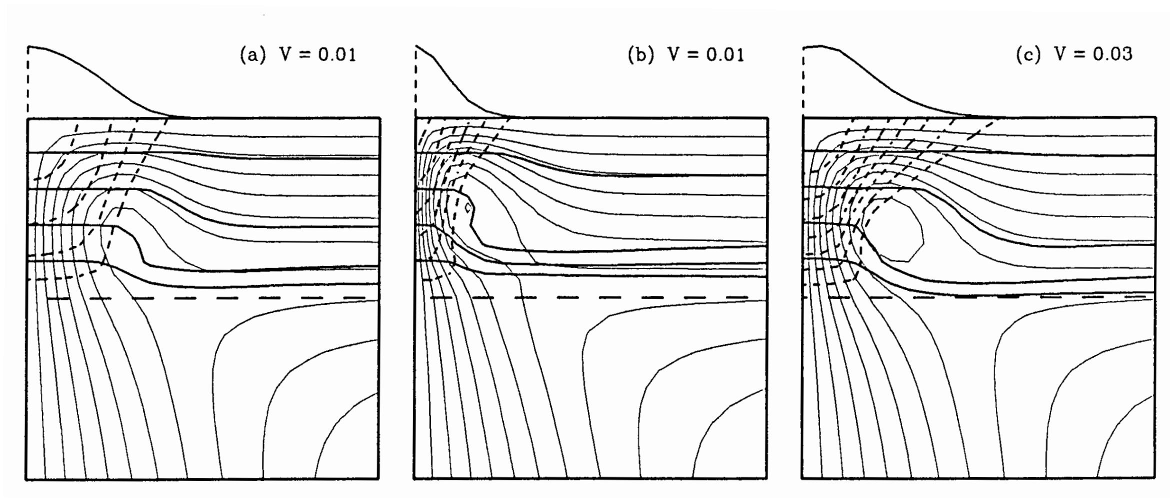



Figure 3.4.1-2: Three calculations of the steady state flow and distribution of liquid and solid beneath a ridge spreading at 1.5 cm/yr. The contours of porosity are at intervals of 1%; of degree of melting, at 4%. The line across the top shows the rate of eruption of magma as a function of distance away from the ridge. The flow model includes not only thermal and compositional effects on buoyancy, but also includes the percolation of magma through the 'solid' matrix beneath a spreading ridge. The cases correspond to different solid viscosities and permeabilities.

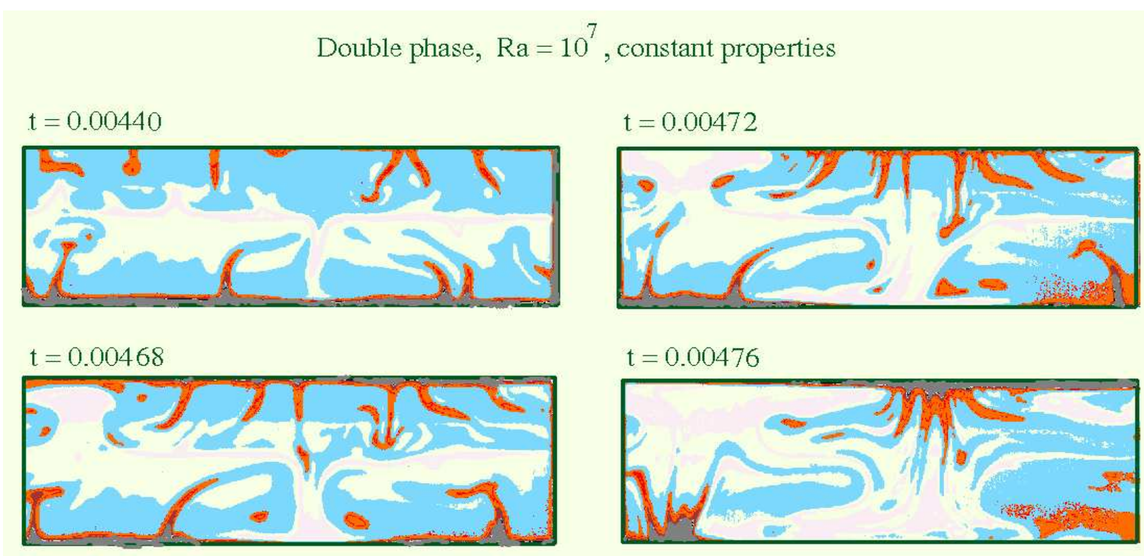



Figure 3.4.1-3: Convection in a box with two phase boundaries, showing a catastrophic breakdown in the initial, layered convection pattern to a single layer pattern that penetrates the phase transitions. Parameters are generally representative of the Earth, and the total time elapsed represents around 20 My.

face motion, "strike-slip" like motion which is not excited in systems with azimuthally uniform rheologies. Figure 3.4.1-5 shows the flow in a model which includes the effects of plates through

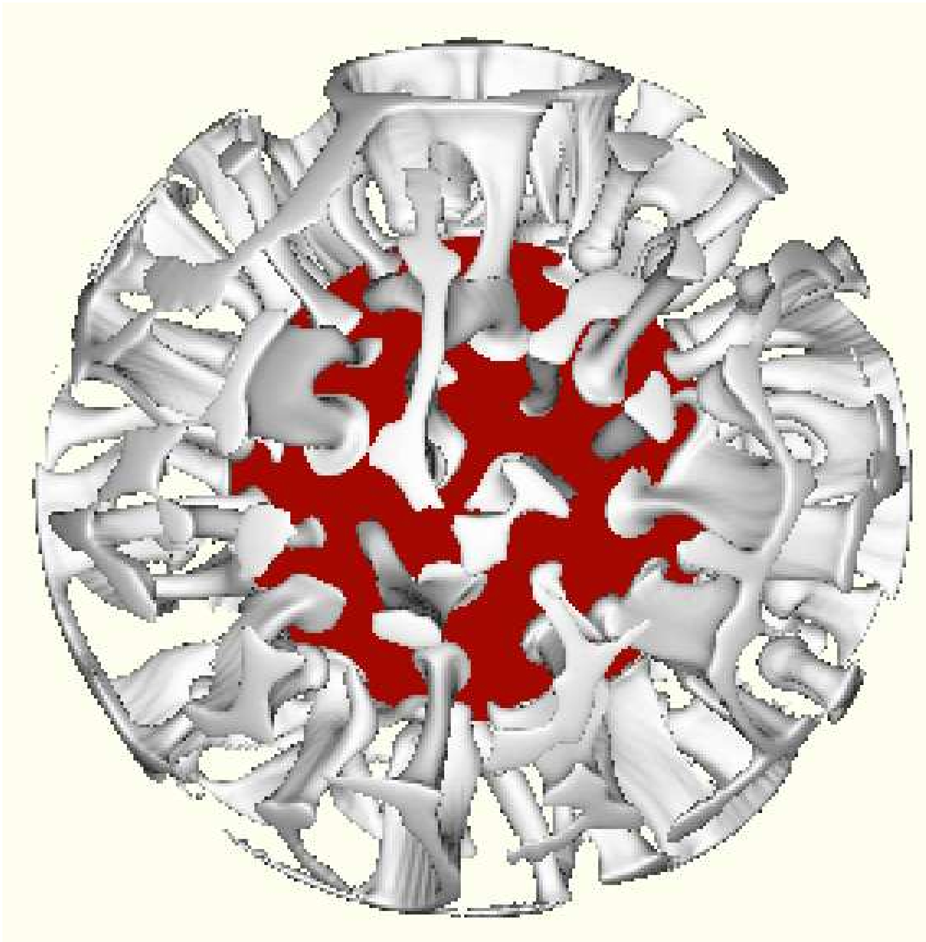


Figure 3.4.1-4: Typical frame from a simulation of three-dimensional, spherical–shell, compressible mantle convection, run on the Intel Touchstone Delta parallel supercomputer at Caltech. The resolution is 384x192x41 grid points. Internal heating accounts for 85% of the surface heat flux and the volume-averaged Rayleigh number is $1.5 \cdot 10^7$. Shown is a surface of constant entropy perturbation relative to the horizontally averaged ($l = 0$) state, representing cold downwellings. Linear, sheet-like downwellings near the surface break up into cylindrical downwelling plumes as they descend. By Paul Tackley, David Stevenson and Gary Glatzmaier.

specifying plate–like velocity boundary conditions at the surface; this allows divergent, convergent and transform boundaries to be included.

Such models are beginning to elucidate how mantle convection drives plate motion, and how the presence of plate influences mantle flow. For example, the presence of plate requires a *toroidal* component of flow, which is completely unrelated to the convective flow driven by temperature anomalies. This added component of flow is most important at and near the surface, and may influence processes such as mixing of geochemical anomalies in the upper mantle.

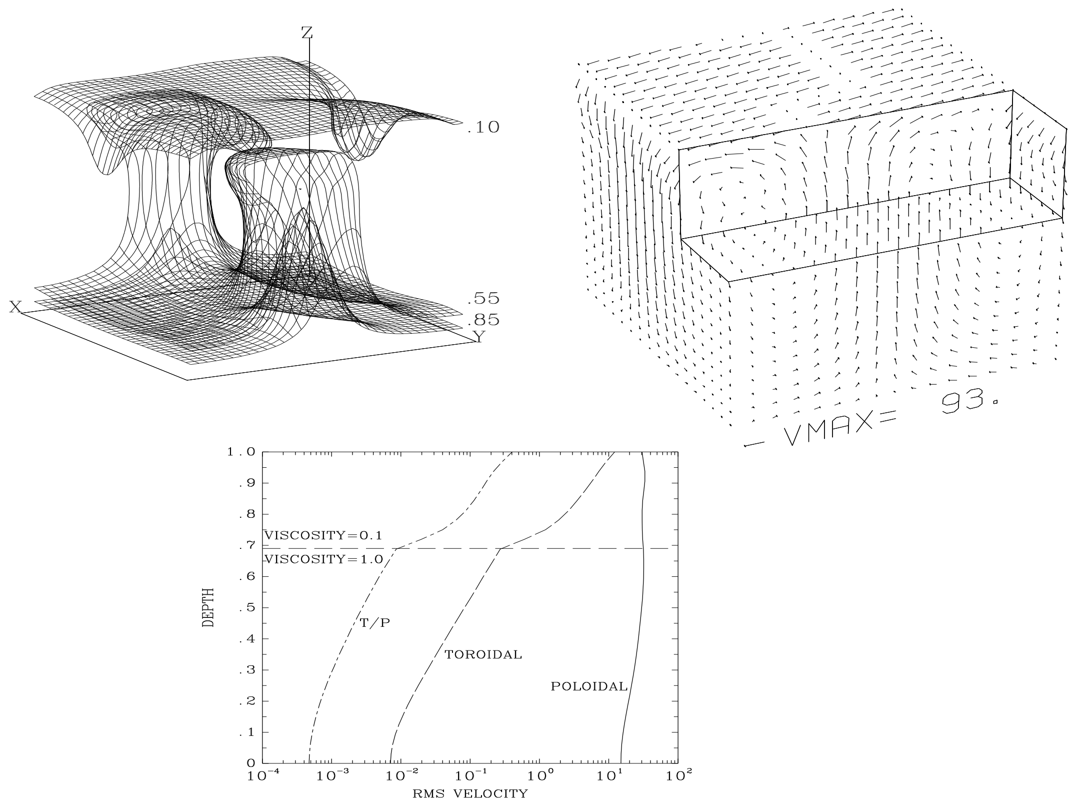



Figure 3.4.1-5: Temperature contours, velocity field, and rms velocity in the poloidal and toroidal velocity field as a function of depth. The flow model uses velocity boundary conditions at the surface to simulate plates, including transform-like boundaries. The viscosity of the upper layer is 1/10 the viscosity of the lower layer. The toroidal field is predominantly confined to the upper layer by the viscosity contrast.

### 3.4.2 Large–scale convection, seismic heterogeneity and plates

Mantle flow, including plate motions, is the direct result of body forces induced by lateral variations in density. Since the nonhydrostatic geoid represents an integral of these density contrasts, one might expect a rather straightforward correspondence between plate motions and the geoid. The long-wavelength variations in the nonhydrostatic geoid (Figure 3.1.1-5) and plate tectonics were discovered concurrently; the lack of a better association between plate tectonic features and the long-wavelength geoid variations has been a long-standing puzzle. Note, for example, that there is no clear correlation between the geoid and spreading centers. While there is a clear correlation between subduction zones and geoid highs, there is also an association between geoid highs and hotspot provinces. How can geoid highs, indicative of excess mass, be associated both with cold downwellings and hot upwellings?

Spectacular progress in understanding the origin of these geoid variations, with major implications for mantle dynamics, has been made by combining recent inversions for the seismic velocity structure of the mantle and 3-D mantle flow models to predict mantle flow and the long-wavelength variations in the geoid. Flow driven by internal density heterogeneity leads to dynamic topography at the surface and the core-mantle boundary. The mass anomalies associated with this dynamic topography have an influence on the geoid comparable in magnitude and opposite in sign to that of the density contrasts driving the flow, so that the total geoid is a rather small difference of large numbers. The key breakthrough has been the recognition that the amplitude of the dynamic topography, and hence the sign of the net geoid anomaly, depends on the depth and wavelength of the density anomaly and on the viscosity variation within the mantle. Thus, if the interior density field is known, the geoid provides a rather sensitive probe of mantle viscosity structure. Figure 3.1.1-5 illustrates how well the observed geoid can be modeled using this approach. In this model, there is an increase in viscosity from the asthenosphere to the lower mantle by a factor of 300. This viscosity structure allows geoid highs to be produced both by the long-wavelength slow velocity features in the lowermost mantle beneath the hotspot provinces and by the intermediate wavelength density anomalies inferred for subducted slabs in the upper mantle.

Computation of the dynamic topography is an integral part of the geoid modeling. As discussed previously, the largest seismic velocity variations are in the uppermost mantle, where, for example, the shear velocity variation between shields and oceans or tectonically active areas is $> 8\%$ (Figures 3.2.1-2 and 3.2.3-2). If density/velocity scalings appropriate for temperature variations alone are used, the dynamic topography has an amplitude of several kilometers, in violation of constraints from continental hypsometry and sea level variations. Thus there must be a partially compensating compositional effect on density and velocity (the "tectosphere" hypothesis). Sorting out the effects of temperature and composition in the observed spatial variation of seismic velocities, as well as understanding the history and dynamics of the continental tectosphere, represent major challenges in Earth dynamics that require an interdisciplinary approach.

Such calculations rely on a wide range of data from several disciplines. Mineral physics data that have been incorporated include density jumps and Clapeyron slopes for phase transformations, depth variation of thermal expansion and depth variation of rock rheology. However, among these, rheology has been poorly constrained, and its role on mantle dynamics has not been fully explored. Important progresses in rock rheology that have occurred very recently include the discovery of a broad correlation between crystal structure and rheology and of the possible role of grain–size reduction on rheology of a subducting slab. These two findings suggest that rheology of mantle materials in the transition zone and the lower mantle will show complicated changes with depth that will have profound effects on mantle dynamics, especially on the fate of subducting slabs. Incorporation of these new findings in computer modelling will be critical to our better understanding of mantle dynamics.

The key logical step in interpreting seismic tomography is to understand the correlation of velocity anomalies and the nature of convection. Velocity anomalies have usually been interpreted in terms of temperature (or density) variation using older laboratory data (Birch's law or equivalents) on the temperature effects on seismic wave velocities measured at low pressures and at high frequencies. However, it is recognized that the temperature derivatives of velocity will decrease significantly with depth. Also, anelasticity will significantly increase the temperature derivatives of velocity where attenuation is large, such as the upper mantle. Thus the ratio of velocity anomaly to density anomaly will decrease significantly with depth. Incorporation of these and other effects in cooperative research among mantle dynamicists, seismologists and mineral physicists will be important to make better use of seismic tomography.

A particular challenge is to relate the mantle structures inferred from seismic tomography to present-day plate motions. One might naively expect that the association would be simple (although the difficulty in understanding the geoid in terms of plate tectonics alone argues against a very straight-

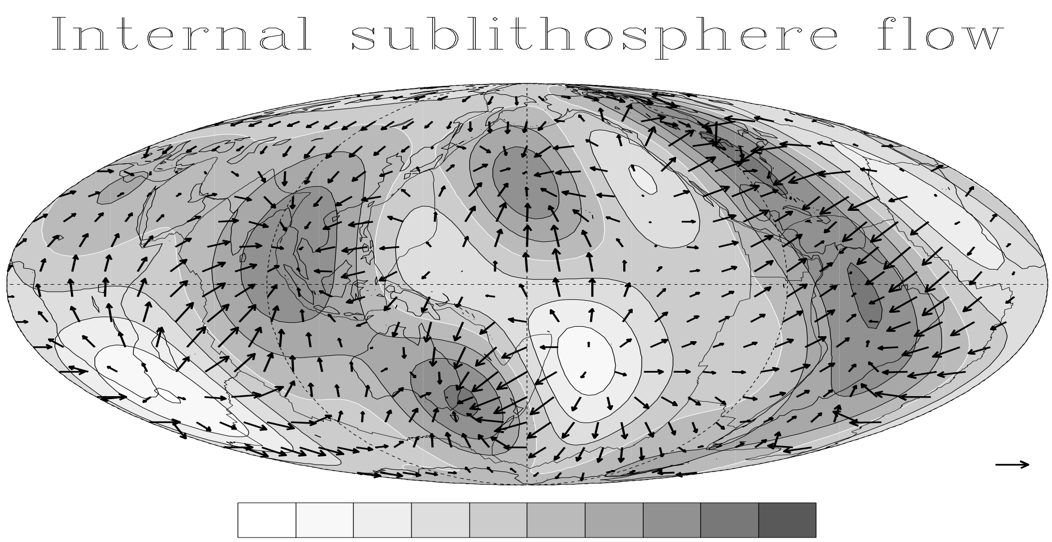



Figure 3.4.2-1: A model flow field, calculated at a depth below the lithosphere, driven by density heterogeneity inferred from recent global tomographic model. Horizontal velocities are shown by arrows, while contours give the radial component of velocity.

forward explanation). For example, Figure 3.4.2-1 shows the flow field just below the lithosphere driven by density heterogeneity inferred from a recent global tomographic model. Horizontal velocities are shown by arrows, while contours give the radial component of velocity. As was the case for the geoid, there is little association of vertical flow with plate boundaries. Ridges are remarkable for their lack of association with upwelling flow. Very few subduction zones have significant downwellings; indeed, the most seismically active subduction zone, the Tonga arc, overlies an upwelling, which extends through the Philippines to Japan. Both the Pacific and African plates have upwellings roughly centered beneath them, with the net traction exerted by mantle flow much smaller than the rms traction. As discussed below, the heterogeneity structure of the lower mantle seems to be more closely related to ancient than to current plate configurations.

### 3.4.3 Geological history of plate motion, surface tectonics and subduction

It has been almost three decades since the revolution of plate tectonics revealed the nature of the surface motions of our planet in startling detail. Not only could plate tectonics describe the present-day motions in terms of rigid plates, but the seafloor record of magnetic anomalies allowed reconstructions of past configurations of plates and plate motions as far back in time as 200 million years. Plate motions and plate boundaries for the fairly recent past (0-64 Ma) are shown in Figure 3.4.3-1. Viewing plate tectonics as the surface manifestation of convection in the Earth's mantle, this history of plate motions is one of the most fundamental constraint on the dynamics of the Earth's interior. Whatever models are constructed for mantle dynamics must explain the observed plate motions.

Until very recently, geodynamical modelers have concentrated on explaining the present-day snapshot of plate motions in terms of dynamical forces acting on plates from 'slab pull' and 'ridge push',

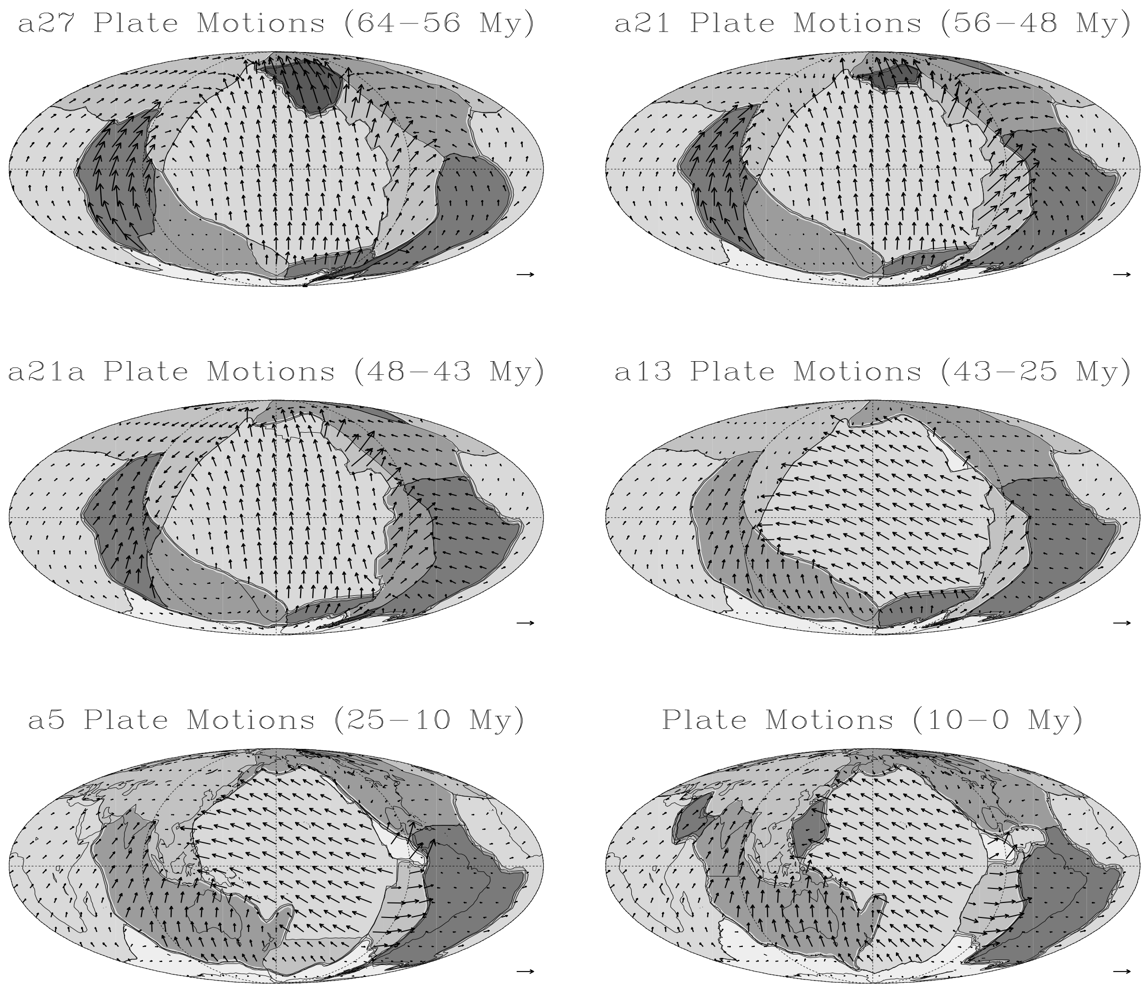



Figure 3.4.3-1: Cenozoic plate reconstructions and plate motions. The center of each figure is 0° N 180° E. The velocity scale is the same for each figure.

as well as from interior density contrasts inferred from seismic tomography. These models have been fairly successful, and Figure 3.4.3-2 shows a comparison between a recent plate motion model and observed present-day plate motions. So far little work has been done to understand past plate motions, and we are not yet able to explain the abrupt changes (reorganizations) that have governed the dynamics of the plate-mantle system. Recently geodynamicists have begun working with the geologists who perform plate reconstructions to get the temporal constraint of past plate motions into the mantle dynamics problem. The initial results from this new marriage of observations and theory are very promising.

The plate tectonic process most obviously related to the dynamics of the Earth's deep interior is subduction. Compelling arguments can be made that subducted slabs are a primary source of mantle heterogeneity and thus provide the main driving forces for mantle convection. The recent history of the subducted slab buoyancy forces can be tracked with confidence for about the past 120 million years using plate reconstructions. The global pattern of subduction is found to have been remarkably stable during this time, and it also explains quite nicely some features of the large-scale

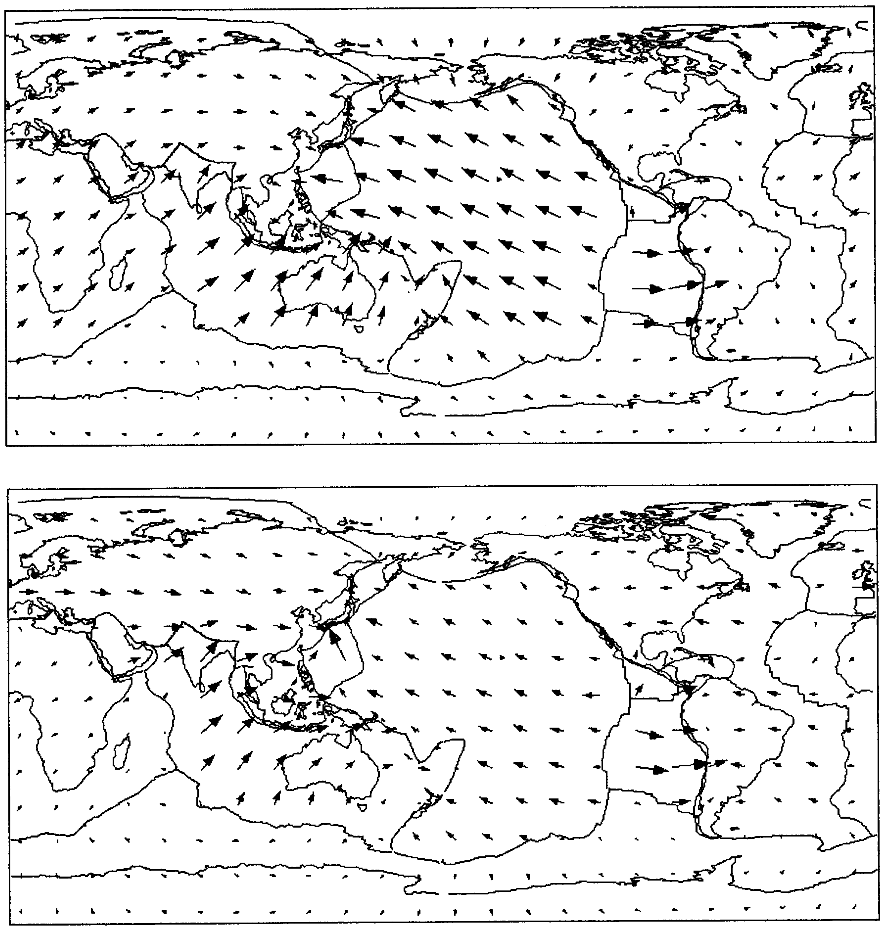


Figure 3.4.3-2: Top panel: observed present-day plate motions. Bottom panel: simple plate motion model, with internal buoyancy forces specified by subducted slabs and variations in oceanic plate thickness.

lateral structure of the mantle. Figure 3.4.3-3 shows a comparison of the distribution of subducted slabs (referred to fixed hotspots) with the global pattern of seismic velocity anomalies, the shape of the Earth's gravitational field, and the global distribution of volcanic hotspots. The correspondence among these four fields implies that the primary heterogeneity structure of the mantle is controlled by the introduction of cold slabs into the deep mantle at subduction zones. Thus we can now make a direct connection between the recent history of plate tectonics and mantle convection.

There is also evidence for some intriguing differences between present and past plate motions. First, the global rate of plate motions has slowed by almost a factor of two since 120 million years ago, and this is associated with a long-term drop in sea level by almost 200 meters. Thus plate tectonics and mantle convection appears to be episodic. In addition to examining the overall rate of plate tectonics, geodynamicists have devoted a great deal of attention to the character of plate motions, especially the relationship between the type of motion that results in convective heat transport (spreading ridges and subduction zones) and the type of plate motion that mainly dissipates mechanical energy (transform or strike-slip boundaries). These components of motion

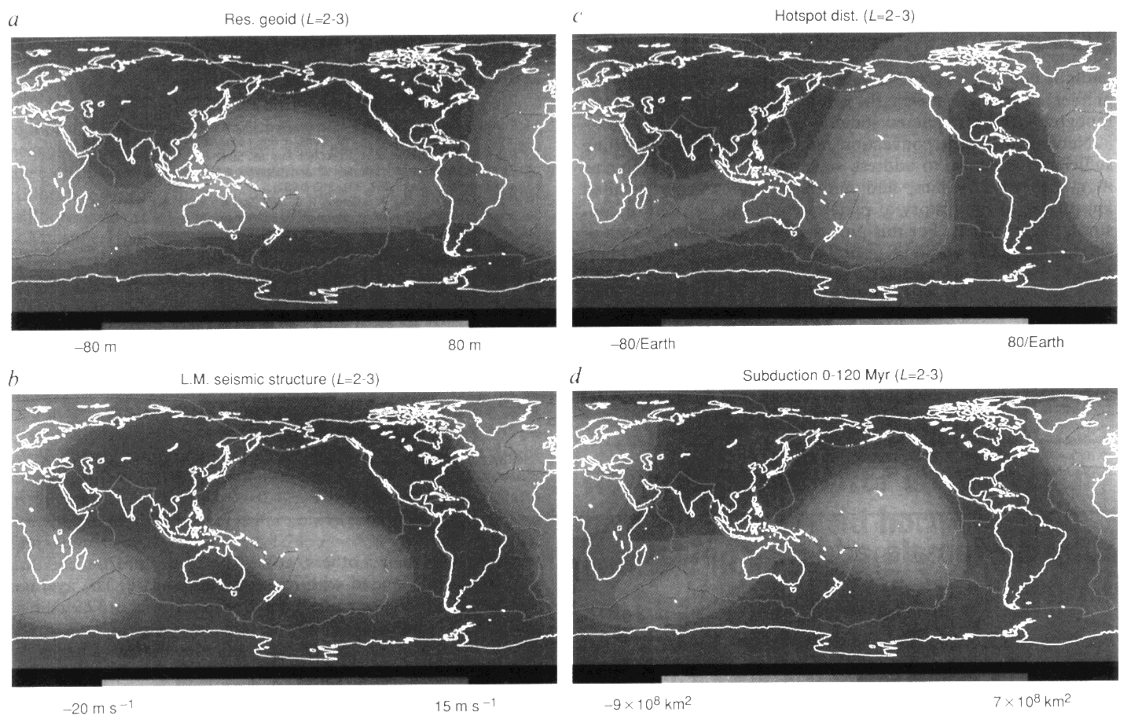



Figure 3.4.3-3: Comparison of spherical harmonic components (L=2,3) of: (a) observed geoid corrected for hydrostatic figure and upper mantle slab signal; (b) lower mantle seismic P-velocity model; (c) hotspot distribution; and (d) time-integrated flux of subducted slabs since 120 Ma calculated in the hotspot fixed reference frame. The patterns are all similar.

are formally represented by the poloidal (spreading/convergence) and toroidal (transform) field of surface velocity, which are much akin mathematically to the spheroidal and torsional modes of seismic free oscillations. Figure 3.4.3-4 shows a recently calculated history of toroidal/poloidal partitioning of global plate motions for the past 120 million years, along with estimated 95% confidence intervals. Surprisingly, the rapid increase in global plate motions as we go back in time into the early Cenozoic and late Mesozoic comes almost entirely in the poloidal components of plate motion, with little associated increase in toroidal or transform-type motion. As yet there is no dynamical explanation for this observation, but it is apparent that the present-day regime of plate motions is, at best, only a weak guide to the past. By implication, convection in the mantle associated with plate motions may be equally variable.

These basically geological observations can only be understood by modeling the dynamics of the mantle on a global scale. Only recently have computer models begun to approach sufficient resolution to address such problems, as discussed in the previous section on large-scale convection modeling. Progress in this area will come through cooperative efforts among a broad range of disciplines: geologists performing plate reconstructions and documenting past tectonic events, modelers using this information to constrain the surface motions of the global mantle convection system, seismologists further defining the present-day structure of the mantle, and high-pressure physicists constraining the mineralogy and rheology of cold, differentiated slab material as it sinks into the mantle. It is in some sense telling that the history of plate motions has been available for almost

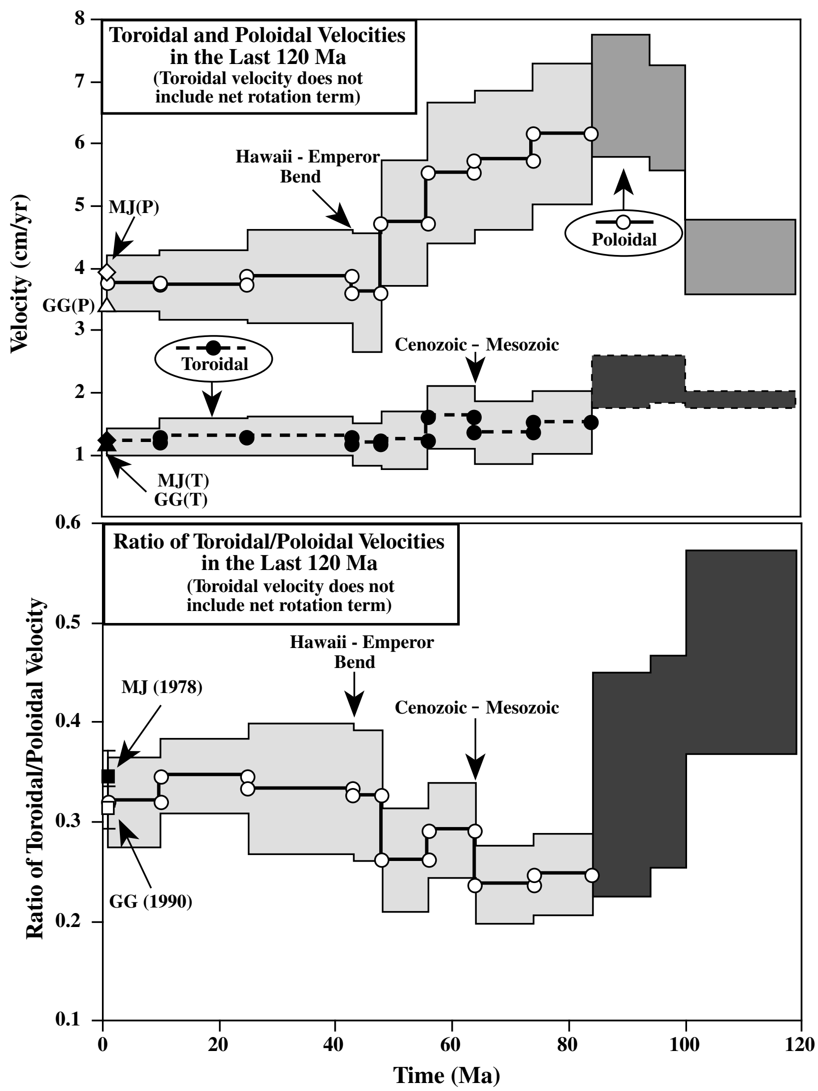



Figure 3.4.3-4: Toroidal (solid circles, dashed lines) and poloidal (open circles, solid lines) velocities through time, net rotation of the lithosphere not included. The circles mark the beginning and end of each stage. The light hatched areas around the solid and dashed lines represent the confidence contour on the velocities. The close hatched areas slanting to the right are the range of poloidal velocities and those close packed slanting to the left are the range (not formal uncertainties) of toroidal velocities from 84–119 Ma, given two choices of poles. Two alternative models for present-day plate motions are also indicated.

two decades, yet only during the past 2–3 years have geodynamicists tried to use this information quantitatively. This delay is in no small part due to the separation of two communities of scientists across disciplinary lines, with separate funding programs and research agendas. The CSEDI program will have a major impact on unifying geologists and geophysicists exploring the dynamics of the plate-mantle system.

### 3.4.4 Deep earthquakes and properties of subducted lithosphere

Each year, approximately 200–300 $km^3$ of oceanic lithosphere is consumed along subduction zones worldwide and the sinking of this volume of cold, dense crust and mantle represents the greatest known concentration of viscous dissipation of potential energy in the Earth. This geodynamic setting produces a unique distribution of intermediate and deep earthquakes that represents about 10-20% of the global seismic energy release [Figure 3.4.4-1]. The distribution and radiation patterns of deep earthquakes are not only revealing of the geometry and physical conditions of subduction, but deep earthquakes are also the best sources of elastic wave energy to probe the seismic velocity structure of subduction zones.

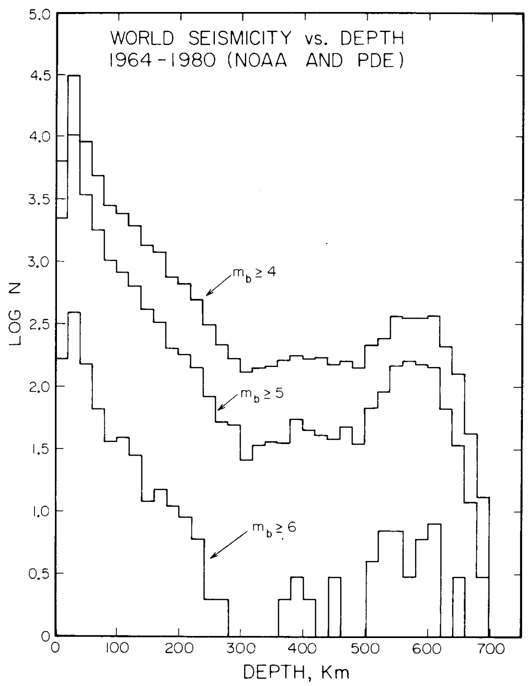



Figure 3.4.4-1: The worldwide earthquake distribution as a function of depth for the period 1964–1980, summed over 20 km intervals. The number of earthquakes decrease with depth above the transition zone, and increases slightly above the 670 km discontinuity, where seismicity ceases.

Deep earthquakes are shear instabilities with predominantly double–couple type focal mechanisms that typically display a pattern of down-dip compression. The source spectra of deep earthquakes are similar to shallow events but broadband waveforms of events below 475 km indicate that rise times of many events are about half those for shallower earthquakes. This observation, coupled with the lack of aftershocks after deep events, suggests that the physical mechanism of deep faulting differs from shallower earthquakes. The distribution of earthquakes in thin slab-like layers and the regional coherence of focal mechanisms suggest that the forces responsible for the stresses internal to descending slabs are regional in extent [Figure 3.4.4-2]. These forces include (1) the viscous forces resisting plate penetration, governed by the rheologies of mantle rocks and minerals, (2) the body forces connected with the negative buoyancy of the colder, denser slab, compared to the mantle it penetrates, including the density effects of phase transformations in the slabs, (3) thermodynamic forces associated with thermal expansion, and internal phase transformation strains.

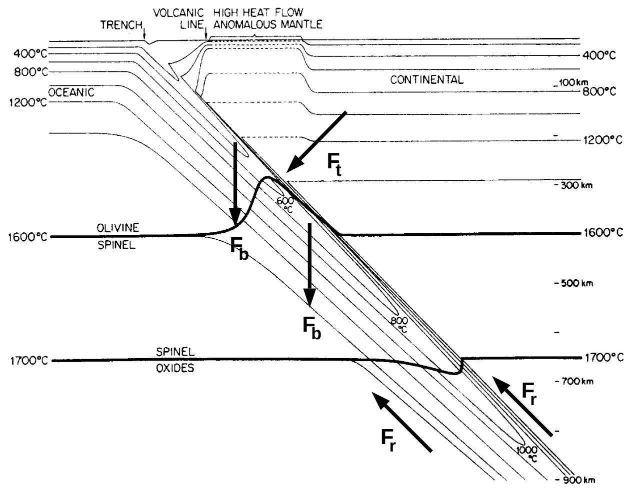



Figure 3.4.4-2: Thermal structure of subduction zones, showing model calculations of the temperature and mineral phase distribution in a subducting slab. Also shown diagrammatically are the forces resisting plate penetration $F_r$, the body forces $F_b$ associated with the density contrasts between the cold, denser subducting slab, and the thermodynamic forces $F_t$ caused by the heating and thermal expansion of the slab and the stresses connected with the transformation volumetric strains.

For many years, it has been proposed that phase transformations within the slabs are related to deep earthquakes. However, it is only recently that experimental studies have been performed to determine whether such mechanisms could give rise to this sort of energy release. Mechanical property measurements are being made on a variety of materials that provide reasonable analogs for the minerals (notably olivine) in the interior of the subducting slab. The results of these studies suggest that olivine may be retained metastably within the slab interior until transformation to the spinel structure by a faulting mechanism that has been correlated with acoustic emissions in high-pressure apparatus. Another mechanism for deep earthquakes has been proposed from high pressure measurements of mineral behavior in the diamond anvil cell. Acoustic emissions during thermal treatment of serpentine have been correlated with the dehydration and amorphization of serpentine, suggesting that large scale transformation during subduction could give rise to earthquakes. It has also been argued that both the serpentine dehydration mechanism and the olivine–spinel transformation give rise to deep earthquakes during subduction, only at different depth ranges.

Of great interest for testing different models of earthquake generation and deformation of the subducted lithosphere are several deep earthquakes which lie "outside" of slabs. Such events have been identified beneath Spain, beneath the Fiji plateau, near the Tonga and Bonin slabs, and recently beneath Sakhalin Island and southern South America [Figure 3.4.4-3]. With exception of the three Spanish earthquakes, these events are associated with seismically active slabs, but are located a few hundred kilometers horizontally "in front of" the main slab seismicity, at depths greater than 500 kilometers. One suggestion is that these events indicate large amounts of horizontal shearing of the slab in the layer above the 670-km discontinuity, but this suggestion provides no explanation for the length of the offsets in seismicity which appears to be similar in several locations. Clearly, the locations of these events are functions of the mineralogy, strain field and temperature in the transition zone, and they therefore represent observational constraints for theories of earthquake

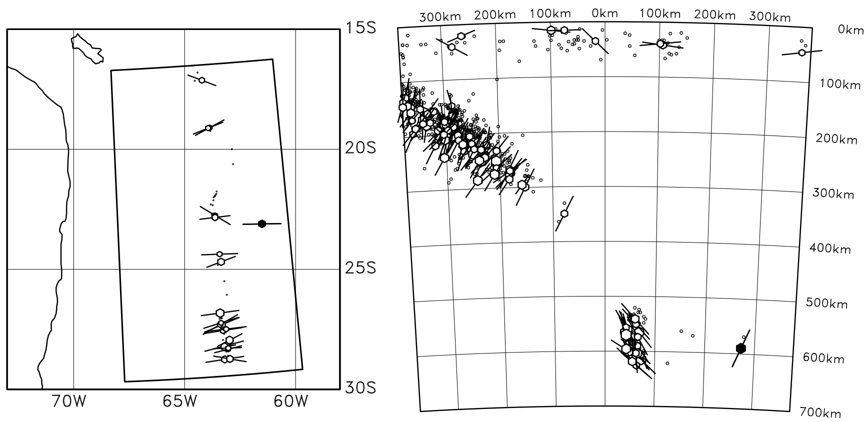



Figure 3.4.4-3: Map view and cross section showing the location of the anomalous deep earthquake beneath South America in 1989 in relation to previous seismicity. Small dots represent hypocenters from the ISC catalog, and hexagons show earthquakes from the CMT catalog. In the map view $T$-axes of the events are shown, and in the cross section $P$-axes. Before the anomalous event (filled hexagon) occurred, the Benioff zone was clearly defined by the seismicity as a nearly vertical thin sheet. The event in 1989 is located 200 km in front of this "slab", and the $P$-axis of the focal mechanism suggests a stress field different from the common down-dip compression.

generation at great depths, and the flow associated with the subducting lithosphere.

Resolution of the questions pertaining to the origin of deep earthquakes requires a broad interdisciplinary approach. Details of source mechanisms are required for actual deep seismic events; potential sources of moment release require investigation using high–pressure and high–temperature mineral equilibria and kinetics; mechanisms of activation or reactivation of faults within slabs necessitate rheological studies during phase transformation; and geodynamic modeling of the processes of slab subduction and penetration into the mantle and transition zone are necessary to provide constraints for the mineral physics measurements. Through such an interdisciplinary approach we should not only derive a greater understanding of the source of deep earthquakes and the mechanics of subduction, we may also resolve questions about slab penetration of the transition zone and lower mantle, and provide some insight into the scale of mantle convection.

### 3.4.5 Subduction and slab fate

The recognition that intermediate and deep focus earthquakes occur in regions where cold oceanic lithosphere has sunk into the mantle played a major role in the evolution of the theory of plate tectonics in the 1960's, and confronted geophysicists with the challenge of determining the structure and ultimate fate of the downwelling material [Figure 3.4.5-1]. The importance of this issue for mantle dynamics and thermal evolution of the Earth has spurred the development of many geophysical approaches to determining the structure of subducted lithosphere, and rapid advances have ensued. The problem is especially challenging in that slabs are complex, relatively small three–dimensional structures embedded in a heterogeneous planet.

Deep earthquake locations are the most direct tracers of subducting slabs, but these terminate by

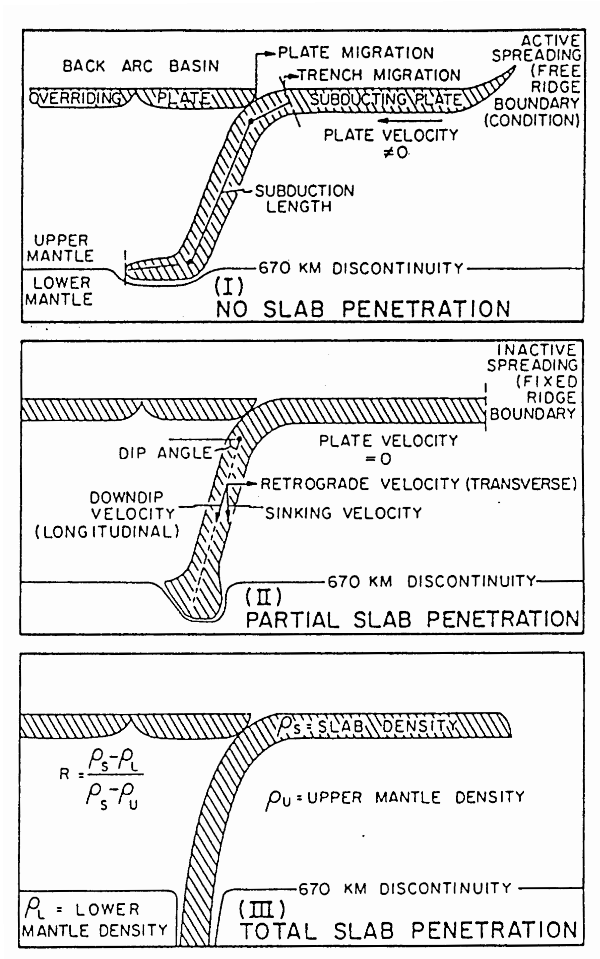



Figure 3.4.5-1: A highly schematic representation of possible fates for subducting lithospheric slabs.

a depth of 700 km, probably as a result of phase transformation in the slab. Mapping the aseismic extension of the slab can be done by seismic tomography. The downwellings are imperfectly sampled by the sparse seismic wave coverage provided by natural seismicity and seismic observatory distributions. Nonetheless, seismological models with detailed three-dimensional elastic velocity structures of deep slabs have been developed by seismic wave analysis [Figure 3.4.5-2], and these models have many implications for the dynamical, thermal and chemical state of the sinking lithosphere. As might be expected for any such complex undertaking, substantial disagreements over the interpretations of the seismic models, and even questions about the basic seismological data sets and imaging procedures, still remain.

On the basis of the current seismic images it does appear that slabs descending through the upper mantle may encounter some resistance against penetration into the lower mantle. This is apparent in deflection of both the seismically active and aseismic extensions of slabs in several regions. A flat lying-slab near the base of the upper mantle is indicated in some detailed tomographic studies, although high velocity anomalies are found in the lower mantle beneath some seismic zones [Figure 3.4.5-2]. A key question is whether these represent slab penetration or lower mantle downwellings caused by slab cooling from above. The interaction of a cold slab with mantle phase transitions is an important aspect of this problem.

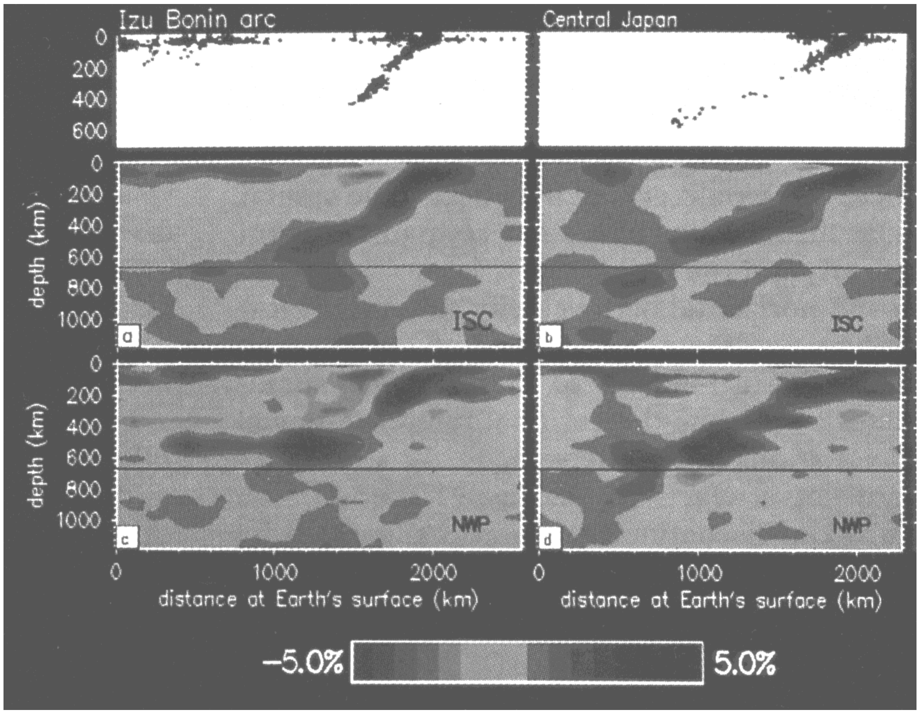



Figure 3.4.5-2: Seismic tomographic images of subducting lithosphere beneath the Izu Bonin arc (left) and central Japan (right). The upper figures (a,b) show anomalies referred to the Jeffreys–Bullen travel times, and the lower figures (c,d) are referred to a more recent travel time model. The darker areas indicate fast velocity regions, which correspond to the subducting lithosphere. Note that it appears that both the Izu and Japan slabs appear to spread out somewhat at a depth of 670 km (horizontal line) but also appear to also penetrate into the lower mantle. The results depend somewhat on the choice of standard model.

In addition to seismic tomography, petrological modeling of subducting slabs is being pursued. While a slab may have a similar bulk composition to the surrounding upper mantle, it has undergone additional chemical differentiation. Thus, a special suite of phases associated with the oceanic crust and the depleted lithosphere must be considered. It is generally agreed that these slab components would become neutrally buoyant in the mantle transition zone if they completely thermally equilibrated with the surrounding mantle. However, slabs warm up slowly, in part because they entrain a cool fringe of surrounding mantle, and thus they have substantial thermal inertia. As a result, viscous flow calculations that allow for the chemical buoyancy still indicate sufficient excess density from temperature alone for slabs to continue to sink into the lower mantle if there is no strong chemical contrast in the mantle. The evidence for an increase in viscosity of the lower mantle suggests that the slabs will strongly deform if they are able to penetrate, giving complex structures like those in Figure 3.4.5-3. The broad region of cooled mantle bears some similarities to the seismic tomography images.

A new approach of combined seismological, petrological and geodynamical modeling should lead to rapid advances in our understanding of the fate of deep slabs. The interdisciplinary interaction will lead to better model parameterizations for the seismic studies, as well as more quantitative

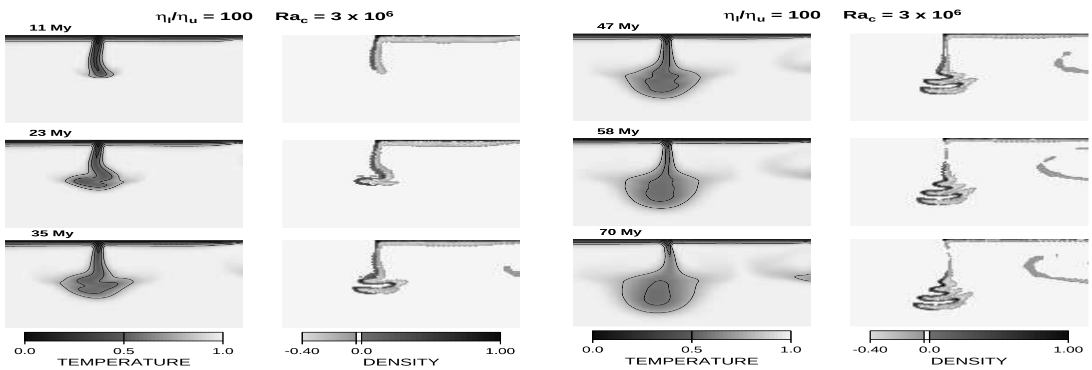



Figure 3.4.5-3: Viscous flow calculations for a chemically differentiated slab sinking into a layered mantle with a factor of 100 increase in viscosity from the upper to the lower mantle. While the slab has sufficient thermal buoyancy to continue to sink, the increased in viscosity slows its descent, bringing about strong deformation of the slab.

interpretations of petrological buoyancy contributions.

### 3.4.6 Plumes and hot-spots

Surface tectonics on Earth are dominated by the effects of plate motions: Ridges, trenches, and transforms form the loci for most volcanism and mountain building. However, there are a number of significant igneous centers, often called hotspots, that are not associated with plate tectonics. Examples include the Hawaiian islands, Iceland, Yellowstone, the Galapagos, and Reunion, and such volcanic centers account for about 10% of the total mantle heat flux. Remarkably, the sites of active volcanism along hotspot tracks appear to remain fixed with respect to each other and independent of plate motions. Furthermore, the lavas produced by hotspots have geochemical signatures often quite distinct from basalts erupted at mid-ocean ridges. The most commonly accepted theory for hotspot formation is that they represent plumes of hot mantle material rising from deep within the mantle, most likely the core-mantle boundary.

Mantle plume dynamics is more difficult to constrain observationally than the dynamics of plate motions: we cannot directly observe the motions of the deep interior boundary layer responsible for plumes. The main evidence comes mainly from geochronological and geochemical studies of lavas erupted along long-lived hotspot tracks, which give a kind of lithosphere-filtered history of plume dynamics. The initial stages of plume activity result in catastrophic volcanic events, such as the Deccan Traps flood basalt, which often precede continental breakup and episodes of rapid plate motions. These events may also cause severe environmental disruption and lead to mass extinctions. After this spectacular initial stage, a mantle plume often settles into a much lower rate of volcanism and produces a trail of volcanos on a moving lithospheric plate, e.g., the Hawaiian-Emperor chain. This phase wanes over a period time until the plume no longer produces volcanism. A number of examples of flood basalt–hotspot track pairs are shown in Figure 3.4.6-1.

Simple laboratory experiments predict this observed temporal behavior for plumes, and Figure 3.4.6-2 shows what has now become the "standard model" for mantle plumes. The sequence of photographs illustrates the development of a large initial plume head, followed by a conduit or tail. Large flood basalt events result from the impingement of the plume head at the Earth's surface,

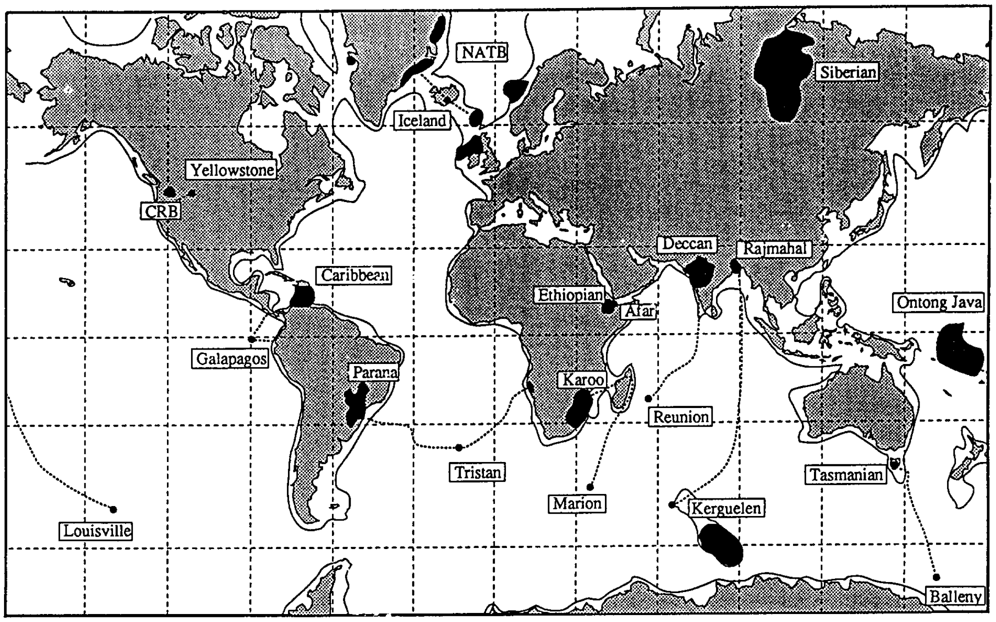



Figure 3.4.6-1: Worldwide distribution of flood basalt provinces erupted in the last 250 million years and associated hotspots (where known or conjectured). Note that while many occur along continental margins, others have formed in continental interiors or in ocean basins.

while the subsequent hotspot track is formed as the lithosphere moves over the trailing plume conduit.

Although the model shown provides a qualitative explanation for volcanism at hotspots, our understanding of mantle plumes is in a stage of infancy. As with the dynamics of the descending 'plumes' we call subducted slabs, models for the physical and chemical behavior of hot rising plumes are as yet weakly constrained and poorly quantified. The list of outstanding questions is daunting: Do plumes really originate at the core-mantle boundary? Do they represent the action of a thermal or chemical boundary layer, or perhaps both? How are the peculiar and highly variable trace element and isotopic signatures of hotspot lavas developed in the mantle? Do they represent 'primitive' mantle material that has never seen the surface, or do they result from processes of chemical differentiation both in oceanic lithosphere and at the core-mantle boundary? How are plumes influenced by phase transformations as they rise through the mantle transition zone? How can mantle plumes remain undeflected by the horizontal motions in the mantle induced by plate tectonics? How hot are plumes, and at what depth do they begin to melt?

Development of a successful quantitative theory of mantle plume volcanism requires interdisciplinary research bearing on all chemical and physical processes occurring between the core and the crust. Geochronological and geochemical studies of hotspot tracks as well as seismic imaging of the mantle beneath active hotspots must be directed toward quantified testable hypotheses based upon dynamical models of plumes. Accordingly, dynamical models must become more sophisticated in addressing processes of melting as well as interactions with the source (CMB) and sink (lithosphere) boundary layers, e.g., plate tectonics and heat transfer from the core. As with modern efforts to model plate motions, we need to develop sufficiently powerful, well-tested 3-D computer modeling codes that can treat the interesting physics and chemistry. This goal is within reach of current

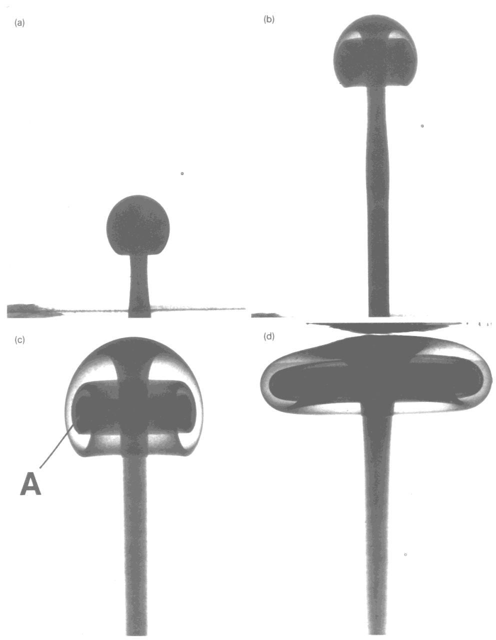



Figure 3.4.6-2: Photographs of a starting plume in glucose syrup at several successive stages during its ascent. Scale is identical in all frames and the head is 6.9 cm across in (c). The hot plume material is dyed red and injected at a steady rate into the colder tank of clear syrup. As the low viscosity plume rises, it forms a large diapiric head followed by a conduit or tail. The plume also loses heat into the surrounding fluid, which becomes buoyant and rises. This produces the pattern of thermal entrainment evident at the point labelled **A**. As the plume reaches the top of the tank, it flattens and spreads beneath the surface.

computer technology, but it is beyond the reach of individual investigators. Instead a sustained, broad-based effort among geodynamicists is required.

### 3.4.7 Earth rotation and Geodesy

Geodetic techniques are able to sense the response of the mantle to internally and externally applied torques. With currently available systems and a data set which now spans over a decade, deviations of the Earth's motion from that predicted by geophysical theories with amplitude of ∼0.3 mm can now be measured, for signals that are coherent with the major tidal forcing signals. Results of this accuracy have been used to infer the flattening of the core-mantle boundary; to bound the anelastic properties of the mantle in the diurnal frequency band; to detect the influence of the solid inner core on the rotational dynamics of the mantle; and to place upper bounds on conductivity at the base of the mantle and the strengths of the magnetic field near the core-mantle boundary. The effects of the oceans have also been detected, and the influence of the Earth's atmosphere are also now becoming evident.

The applications of geodetic systems cover all time scales from the diurnal and semidiurnal bands of the major tidal forces being applied to the Earth to decade duration variations whose study is limited only by the duration of the geodetic data themselves. In the former of these time scales, the

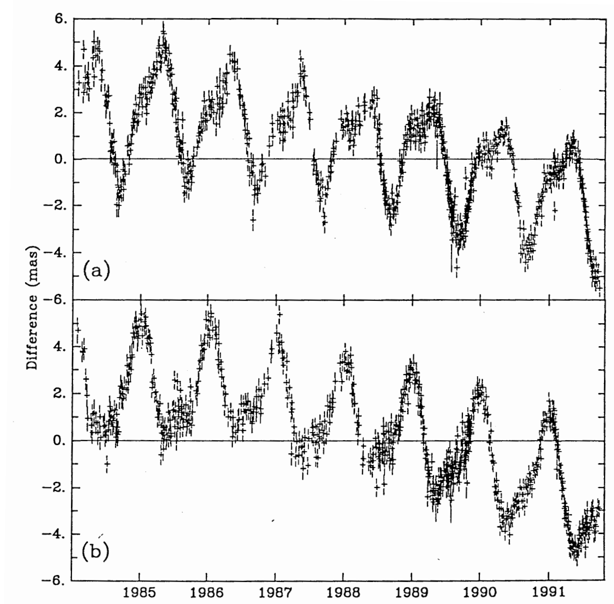



Figure 3.4.7-1: Differences between positions of an axis attached to the mean mantle of the Earth (body axis) in inertial space predicted by the IAU 1980 nutation series and observed with very long baseline interferometry (VLBI). The positions are expressed as two angles: (a) nutation in longitude and (b) nutation in obliquity. One milliarcsecond (mas) is equivalent to 30 mm displacement at the surface of the Earth.

forcing functions are well known and the geodetic systems can measure the response of the Earth to these forces. In the latter of these time scales, the forces themselves are not well understood and geodetic systems provide information about convolution of the forcing function with the response of the Earth.

For deep Earth studies, geodetic measurements can provide accurate information about the dynamical interactions of the fluid core and mantle. Much of this information arises from a resonance in the rotation of the Earth due to the differential rotation of the core and mantle. The torques applied to the mantle by the core are sensitive measures of the flattening of the core-mantle boundary and deformation of the mantle arising from the pressure of at the core-mantle boundary as the elliptical core rotates differentially with respect to the mantle. Since the frequencies of these torques are in the nearly diurnal band, the measurements of the nutations of the Earth and the associated surface deformations provide unique measures of the dynamical mantle properties in this frequency regime. For example, competing models for the frequency dependence of the shear-strain Q of the mantle predict anelastic effects on the rotation whose amplitudes at the surface differ by a few millimeters. While these values are small, they are detectable with current data sets. Similarly, magnetic coupling between the core and mantle could also produce few millimeter deviations which are currently detectable.

The major differences between a geophysical theory for the motion of the Earth's body axis in space and those observed by very long baseline interferometry are shown in Figure 3.4.7-1. The large annual signature (amplitude 2 mas) is interpreted as being due to a deviation of the core-mantle boundary from its hydrostatic shape by about 4.5%. The long period variations reflect deviations in the 18.6 year nutation whose accurate determination is currently limited by the duration of high quality VLBI data. Not so evident in the figure is a semi-annual signal (amplitude 0.5 mas) which arises partly from the excess flattening of the core mantle boundary (0.3 mas), partly from ocean tides (0.6 mas), partly from the anelasticity of the mantle (0.3 mas), and partly from the deviation of the ellipticity of the whole Earth from that computed assuming hydrostatic equilibrium and geophysical models of the density distribution of the Earth (1% deviation in the ellipticity which introduces a signal with an amplitude of -0.4 mas). Although non-hydrostatic models of the Earth derived from seismic tomography have been available for a number of years, a rotational dynamic model for the Earth has yet to be constructed with such data. When such a consistent model is determined the anomalies due to the ellipticity of the whole Earth and fluid core should be eliminated.

Because the forcing functions are known for the nutations, both the in phase and out of phase components of the response of the Earth can be determined, with the latter interpreted as arising from dissipative processes in the Earth. For example, 0.4 mas of the annual signal is out of phase and thought to arise from magnetic coupling between the core and mantle, while other out of phase components are consistent with anelasticity of the mantle.

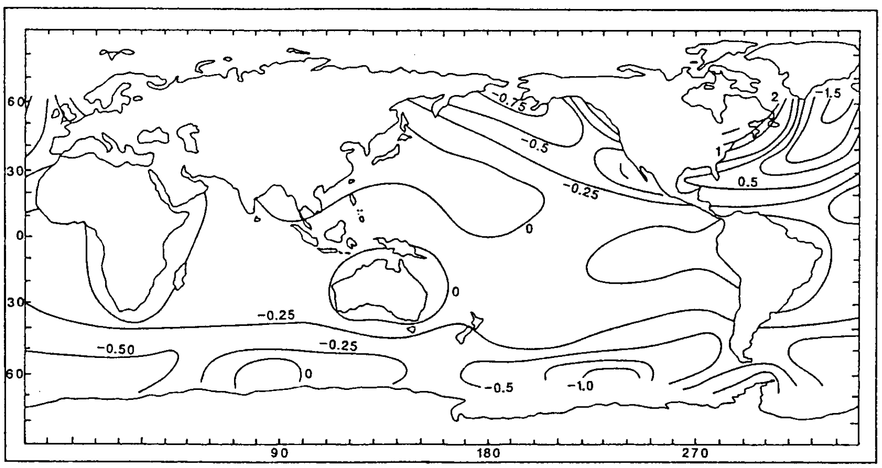



Figure 3.4.7-2: Predicted rates of sea–level change from a model of post–glacial rebound. The contours are in units of mm/year.

The accuracy of these nutation results, along with other rotational components such as diurnal and semidiurnal variations in the rotation rate, is now so high that deficiencies in the accepted tidal displacement models also need to be examined particularly in the light of the effects of mantle inhomogeneities and anelasticity Although these effects are expected to be less than 1 mm of surface displacement, they are within the realm of detectability with the current systems and data sets.

Geodetic techniques can now detect the small motions associated with the changes in shape of the Earth from the isostatic adjustment to the last deglaciation that occurred around 15,000 years ago. The effects are small (less than 1 mm/year), but they are potentially measurable, and they are essential for interpreting measurements of changes in sea level. Figure 3.4.7-2 shows the calculated effect of post glacial rebound on sea level rates of change. These effects depend on the rheology of the Earth's interior, which may also be determined from studies of mantle convection and plate motion. Thus the time scale of the effects ranges from years to hundreds of millions of years.

### 3.4.8 Composition and petrology of the mantle

Is the mantle essentially a homogeneous peridotite from the base of the crust to the top of the core? Or are the chemistries of lithospheric peridotite xenoliths that we sample at the Earth's surface merely good examples of the shallow mantle? Are they in fact poor compositional analogues for the the deeper level transition zone and lower mantle, which may be more similar to chondritic meteorites with less olivine and a lower Mg/Si ratio? These questions, although yet unanswered, address the most fundamental petrologic problem of the Earth's interior. If we are able to determine which of these possibilities is closest to the truth, then we may understand more fully, the processes that transformed primitive solar system material into a terrestrial planet with crust, mantle and core.

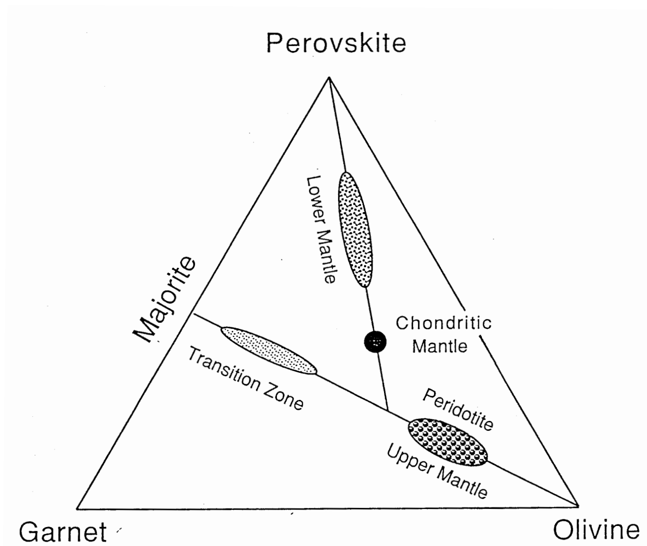



Figure 3.4.8-1: Triangular compositional diagram (wt%) with olivine ($Mg_2SiO_4$), garnet ($Mg_3Al_2Si_3O_{12}$) and perovskite ($MgSiO_3$) at the apices. Majorite is shown as a solid solution on the join $Mg_3Al_2Si_3O_{12}$–$Mg_2SiO_4$. The range of compositions for fertile peridotite xenoliths is shown schematically by a dotted oval field labelled peridotite upper mantle. Chondritic mantle composition is indicated by the black dot, the composition is based on C1I carbonaceous chondrites with Fe removed to account for the Earth's 32 wt % core. Elongate oval labelled "lower mantle" represents a range of possible compositions for a perovskite enriched lower mantle. The other elongate oval labelled "transition zone" represents a possible range of compositions if the transition zone is enriched in majorite.

The proposition that the mantle is compositionally homogeneous is attractive because first order isochemical phase transformations in olivine-rich rock can broadly describe the observed seismic wave velocity jumps at 400 and 660 km. If there were no other lines of evidence on the petrology of the mantle, proposals for abrupt chemical changes at 400 and 660 km or large chemical gradients in the mantle might be rejected as superfluous. But additional evidence on the mantle's composition and petrology does exist, and it is derived from the abundances of elements in carbonaceous chondrites and from experimental high-pressure phase equilibria studies. Carbonaceous chondrites are good analogues for the initial bulk chemical composition of an accreting early Earth because they contain approximately solar abundances of the non-volatile elements and are the most primitive objects yet sampled in the solar system.

High-pressure phase equilibria experiments have established that olivine, garnet (majorite), and Mg-perovskite are dominant crystalline constituents of chondritic and peridotitic compositions with depth in the mantle. Figure 3.4.8-1 illustrates the compositional differences between a Fe-depleted silicate mantle based on carbonaceous chondrites and a mantle composition based on peridotite xenoliths, both of which are cast in terms of olivine, majorite, and perovskite. It can be seen that peridotites are richer in olivine component and poorer in perovskite component than a chondritic mantle. If the Earth's mantle is bulk chondritic, then the peridotite xenolith source region (shallow mantle) must be balanced by a complementary olivine-poor, perovskite-rich region at depth.

The most reasonable location for this region is in the lower mantle, since it is there that Mg-perovskite is thermodynamically stable. Depletion of perovskite component from the upper mantle is not on its own sufficient to match peridotite exactly, an olivine component must also be added to produce the composition of the xenolith source region. The mass balance is complete, and consistent with phase equilibria constraints, if a third component, rich in majorite, is partitioned in the transition zone. A general conclusion from the chondritic mantle proposal is that even though first order isochemical phase transitions occur at 400 and 660 km, chemical stratification of the mantle is required to preserve mass balance. In contrast to a chemically layered mantle, a homogeneous peridotite whole mantle implies that the Earth accreted from material that is compositionally unlike any known chondrite class or mixture of chondrite groups.

The seismic data for deep regions of the Earth is quite precise, but it is difficult to interpret because of the lack of experimental data at appropriate conditions. Inferring the mineralogy and composition of the deep Earth requires joint interpretation of seismic, phase equilibria and mineral physics data. Seismic observations that bear upon this issue include the absolute values of P and S velocities and density as functions of depth, the depth and characteristics of mantle discontinuities, the patterns of aspherical structure and variation in depth of discontinuities, and the depth extent of slabs and plumes. Interpretation of these seismological parameters requires input from convection modeling, phase relations in silicates, and thermodynamics and properties of minerals under extreme conditions.

### 3.4.9 Melting and differentiation of the early Earth

It is now clear that accretion of the planets was a violent, high temperature phenomenon. Recent work on the role of large impacts during planetary formation suggests that numerous collisions with lunar-size objects may have initiated extensive melting of the primordial Earth. [Figure 3.4.9-1] Investigations on the origin of the Moon by a giant impact also indicate that extremely high temperatures may have existed during this proposed event; high enough to melt the entire proto-Earth and vaporize some of the silicate mantle. If the Earth experienced early wholesale melting, then crystal fractionation should control the connection between the initial state of the Earth and the differentiated products.

The structure of the Earth's interior contains clues as to the early evolution of the mantle. The presence of a trace-element enriched crust, a hydrosphere, an atmosphere and an iron-rich core testify to a well differentiated Earth. One question is can the Earth have gone through such a major differentiation and still retain a chemically uniform mantle? The mantle may be turbulent and well-stirred during its early high temperature phases, but at some point crystals and melts will tend to separate from each other. One end-member says that this separation gave a refractory, dense lower mantle and core and a buoyant, olivine-rich upper mantle. Another end-member is

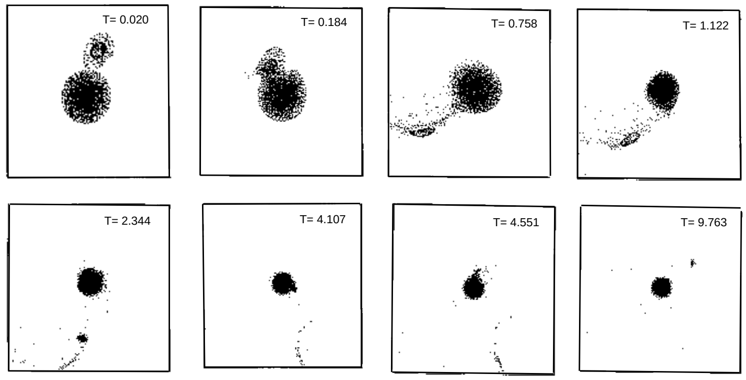



Figure 3.4.9-1: Numerical simulation of the impact of Earth by a body of mass $M_{\oplus}/7$. The initial conditions are zero relative velocity at infinity but the present Earth Moon system angular momentum. The iron cores are circled. Time is given in hours from impact. The clump in the lower right corner of the last frame has exactly one Moon mass (35 particles). There is another 1/2–1/3 Moon mass in a disk around Earth. No iron is in orbit. Subsequent evolution after the final frame is not known. Results courtesy of W. Benz (Los Alamos National Laboratory).

that subduction and recycling tend to keep the mantle homogeneous [Figure 3.4.9-2]. Resolving whether the lower mantle is “primitive” undifferentiated material or the refractory residue of whole earth differentiation requires input from seismology, petrology, geochemistry, cosmochemistry and convection modeling.

Over the past five years there have been dramatic advances made in the application of large volume, solid media, high-pressure technology to experimental petrology. We are now able to begin testing specific proposals for the initial composition of the Earth and possible differentiation schemes that include deep mantle melting, from the perspective of phase equilibrium and geochemical partitioning constraints. One proposal mentioned in 3.4.8 is that the Earth resembles some chondrites in initial composition. One of the the ways in which carbonaceous chondrites (CC) differ chemically from modern upper mantle peridotites that was not explicitly addressed in 3.4.8, is that CC are much more FeO-rich. FeO-rich in this case implies iron in the ferrous state, for the most part, as an essential structural component in silicate minerals. If subjected to crustal or shallow mantle conditions the stable ferro-silicates in a carbonaceous chondrite are primarily olivines and pyroxenes. At higher pressures in the deeper mantle it is expected that ferrous iron resides in garnet, silicate spinel, silicate perovskite, and magnesiowüstite. It has been a commonly held belief that this “’excess” ferrous iron in a chondritic Earth was removed from the silicate mantle and segregated as metallic iron to form the core. Such a mechanism however, could not have operated at the oxygen fugacities present in today’s upper mantle and certainly could not have operated in a body similar to carbonaceous chondrite, the most oxidized of the primitive chondrites.

A requirement for Fe (also Ni, Co, and other moderately siderophile elements) extraction from silicate minerals to form a core the size of present Earth’s is to invoke a highly reducing oxidation state during the early mantle-core evolution. Had the present mantle undergone a single stage reduction reaction to form the core in this way, then a geochemical signature might be evident in the samples of upper mantle peridotites. These hypothetical peridotites would contain olivines with forsterite contents of 98 mol % versus the 90 mol % actually observed, and both $Ni^{+2}$ and $Co^{+2}$ would be wholly missing from the mantle, rather than being at ∼1000’s (Ni) and 100’s

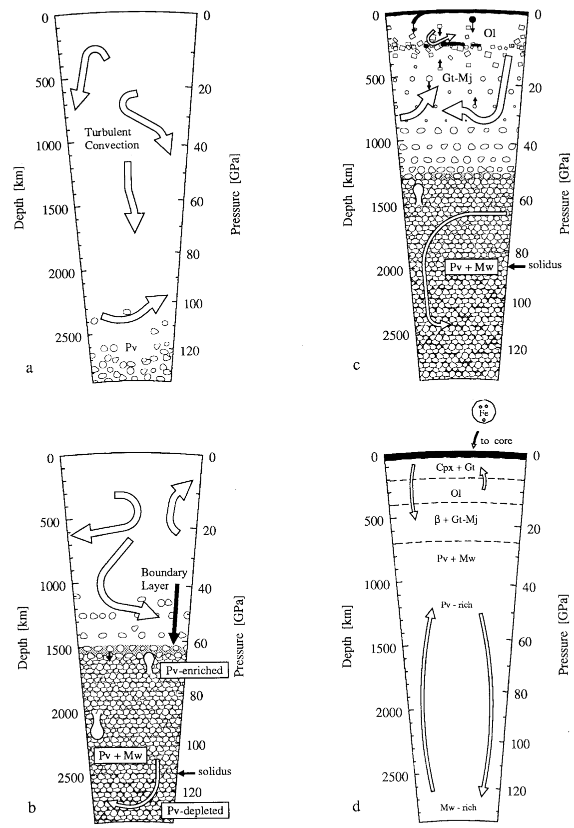



Figure 3.4.9-2: Cartoon snapshots of the evolution of the mantle from an initial wholly molten state. (a) The first crystals to form will be perovskite at the base of the lower mantle. Crystal–liquid fractionation cannot occur although perovskite is likely to be buoyant. (b) In this snapshot, a boundary layer exists in the shallower lower mantle, and perovskite crystals may be capable of settling downward at this boundary. In this shallow region, perovskite–depleted liquid could percolate through the perovskite matrix to be mixed into the convecting liquid above. Below the level of perovskite neutral buoyancy, percolating iron–rich perovskite–depleted liquid could sink. (c) When the upper mantle begins to crystallize, a mechanically unstable crust may begin to form. Stagnant boundary layers on the unmelted foundered crust would allow olivine crystals to segregate from the magma leading to the formation of a dunite septum. Garnet–majorite cannot fractionate until the 'floor' of the magma ocean reaches the garnet–majorite stability horizon. The crystalline deep lower mantle is undergoing subsolidus convection. (d) A schematic representation of the (gravitationally unstable) stratification of the mantle before subsolidus convection and possible rehomogenization takes place.

(Co) ppm trace levels often recorded in xenoliths. To remedy the unrealistically low oxidation state produced in these models, an *ad hoc* late-stage bombardment of fresh oxidized meteoritical material is commonly included in the scenario. This oxidized component is meant to penetrate and mix with the mantle in order to boost the oxygen fugacity back up to appropriate levels.

As an alternative to the "two component" oxidation state model for mantle differentiation and core formation, multi-anvil experiments performed recently at 24, 26 and 26.5 GPa on the Allende carbonaceous chondrite suggest that it may be possible to segregate iron from the primordial mantle to form the core without invoking a highly reduced oxidation state. Instead, a large portion of the iron reaches core depths and is incorporated there not as Fe(Ni)-metal but as Fe(Ni)-sulfide and Fe-oxide. The multi- anvil experiments show that FeO-rich magnesiowüstite is an abundant crystallizing phase at temperatures near the silicate liquidus in carbonaceous chondrite. Coexisting with this silicate-oxide phase assemblage is FeNiS liquid phase. If a chondritic Earth experienced a high-temperature molten stage, then during cooling and crystallization, the segregation of the densest phases (molten Fe,Ni-sulfide and FeO-rich crystalline magnesiowüstite) to the deepest levels of the interior could occur.

It is proposed that magnesiowüstite fractionation may have depleted the initial FeO content of the primitive chondritic mantle and contributed to the formation of the Earth's core. This first approach to the experimental problem assumes for simplicity that the Earth accreted from 100 % carbonaceous chondrite. Because carbonaceous chondrites are the most oxidized of the chondrites, this model also results in the maximum oxygen in the core. If for instance, the model is modified to include some ordinary and enstatite chondrites to the mix, then the amount of oxygen in the core may be lower. The variability of sulfide, carbon and hydrogen contents in chondrites may also be addressed in a similar way to explain the "light" element budget for the core.

Though not stated explicitly in the previous section, the enrichment of the lower mantle in perovskite component and addition of olivine to the shallow mantle are best explained by buoyancy driven crystal fractionation in a partially molten mantle subsequent to core formation. The efficiency with which these cumulate layers may form is still obscure. Crystal settling and layering will depend on aspects such as the rheology of the convecting magma ocean, crystal size, nature of crystal aggregation, and topology of the mantle liquidus and solidus.

*Trace element and isotope evidence:* Nd isotopic studies of the oldest preserved Archean crustal rocks (3.6-3.9 Ga) yield $\epsilon_{Nd}$ values in the range +1 to +4 and have clearly been derived from mantle sources that had a small melt fraction extracted prior to at least 4.2 Ga. The nature of this early melting is still controversial. No samples carrying the signature of complementary enriched reservoir have yet been identified. Three possible explanations for these observations are: i) growth of normal crust during the Hadean (3.9-4.5 Ga) and high recycling of continental crust during the late Hadean and early Archean. ii) the Hadean crust was alkali basalt and was later totally destroyed. iii) cumulate layering in the early mantle due to an early Hadean magma ocean. Beyond the LREE depletion in the Hadean mantle, trace elements constraints for the early mantle are relatively poor. One of the controversial issues is whether there is any evidence in the trace element data for perovskite-liquid fractionation. For example Hf isotope data of 4.1–4.2 Ga old Australian zircons appear to be derived from a source that has a $Lu/Hf$ ratio relatively close to chondritic (but poorly determined) and has been used as evidence against perovskite fractionation in the early mantle. Both better isotopic and trace element constraints as well as refined perovskite liquid partitioning data are required to resolve this issue.

### 3.4.10 Geochemical evolution and fractionation of the mantle

There is abundant evidence that the Earth's mantle is chemically heterogeneous. However, the nature, development, scale, and distribution of this heterogeneity remains controversial. An understanding of the distribution of minor chemical constituents, including the important heat-producing elements K, U, and Th, in the mantle is central to the development of models for the earth's internal structure, dynamics and evolution.

The earliest chemical fractionation of the mantle was a consequence of processes related to the accretion of the Earth and metal segregation to form the core. Partitioning into the core caused very strong depletions of siderophile and chalcophile elements in the early mantle. A significant amount of the budget of certain volatile and siderophile elements may have been added through the accretion of a late veneer of chondritic material. Since then, partial melting in the upper mantle has probably been the primary process causing chemical fractionation in the mantle. This has resulted in two major products over geological time that are available for direct observation and measurements: the continental crust and the oceanic crust. The continental crust has a mean age on the order of 2000 million years, roughly half the age of the Earth, whereas the oceanic crust is rapidly recycled into the mantle and has a mean age of only about 100 million years. The continents constitute roughly 0.5% of the mass of the earth; even so, they contain a substantial fraction of the earth's budget of K, U, Th, and a host of other magmaphile elements that include most of the important tracers we now use to decipher the evolution of the planet. Although major element abundances in the mantle remained essentially unaffected by the extraction of the continents, mantle trace element abundances and distributions underwent dramatic upheavals.

The formation of the continental crust depleted a large part of the mantle in incompatible trace elements, and this depleted part of the mantle is now the source of the basaltic oceanic crust found at mid-ocean ridges (MORBs). The isotopic evidence from the Earth's continental crust and MORBs has established that the continental crust and the source of the oceanic crust are chemically and isotopically complementary in many respects. The isotopic data have also been corroborated qualitatively by the relative abundances of trace elements found in continental rocks and in MORB. The overall major and lithophile trace element chemistry show a surprisingly simple and consistent pattern of complementary enrichment and depletion for nearly all elements for which there are analytical data. Because it is sampled by the world-wide spreading ridge system, the depleted MORB source mantle (DM) must reside in the uppermost mantle. This is shown schematically in Figure 3.4.10-1.

While the formation of the continental crust is essentially a unidirectional process involving the stabilization of relatively light materials at the surface of the earth, the oceanic crust has been created and destroyed many times over. The total volume of oceanic crust produced over the course of earth history is much larger than the continental crust, and would constitute a significant fraction of the mantle, were it stored there permanently. The subduction of the oceanic crust into the mantle provides the principal means whereby materials that once resided at the surface are reinjected into the mantle.

There is a first-order isotopic distinction between the mantle which upwells at ocean ridges and that which supplies basaltic magma to oceanic islands/hot spots (OIBs). Ocean island basalt sources themselves may be classified into various enriched/depleted types of mantle reservoirs (EMI, EMII, DM, and HIMU). While there is general agreement about the origin of DM, the origins of the other OIB source reservoirs are less well understood, and questions of how they originated, and where they are currently situated in the mantle, are a matter of present controversy. It appears that heterogeneities in the ocean island (OIB) sources are probably not all a consequence of partial melting over geologic time. The primary process that appears to be involved is recycling of oceanic and continental crusts/lithosphere. Isotopic systematics suggest a mean life time of about 1–1.5 Ga for the recycled components.

**Chemically distinct mantle components:** Chemical heterogeneities in the mantle, produced by melt generation and extraction, and by the recycling of oceanic crust and sediment over 4.5 Ga, constitute a record of the geochemical evolution of the silicate portion of the planet. Characterization of these heterogeneities, via study of mantle-derived materials at the surface of the earth,

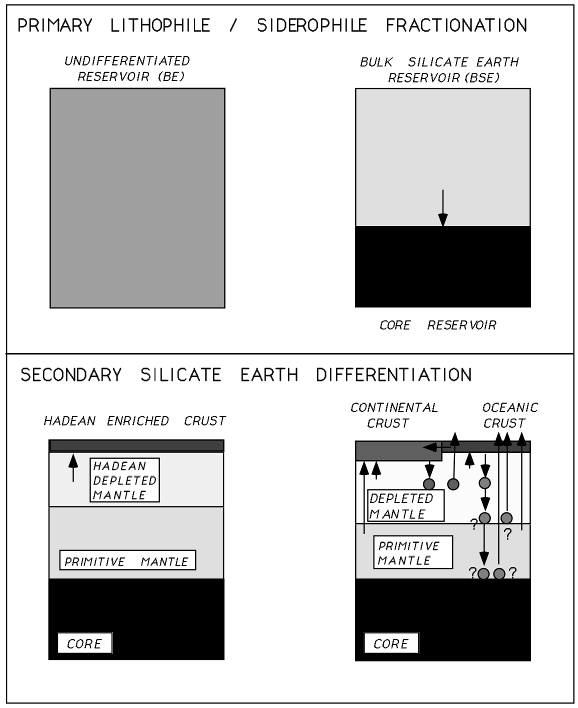



Figure 3.4.10-1: Schematic representation of major processes causing chemical fractionation in the Earth's mantle. Arrows indicate direction of mass fluxes.

is the only means available to read this record. These geochemical results not only provide important tests for geophysical models of mantle melting, structure and dynamics, they also provide an essential element in our quest to understand the processes that have shaped the earth.

*Primitive (or close to) undifferentiated mantle reservoirs:* A fundamental and unresolved question is whether primitive undifferentiated reservoirs still exist in the Earth's mantle. The term "primitive" here refers only to those refractory lithophile elements that are not fractionated relative to chondritic element ratios by either core formation or accretion (U, Nd, Sr, etc.). One of the components observed in OIBs referred to as EMI appears to be slightly modified primitive mantle. This source could have been derived from "primitive" mantle several billion years ago, for example, by very minor changes in Rb/Sr, Sm/Nd, U/Pb and Th/Pb ratios. Other suggestions for the origin of the EMI source, such as mixing of depleted MORB source mantle with recycled oceanic crust, or sediment, seems less likely on the basis of several trace element constraints. Some continental flood basalts also appear to be derived from primitive or near primitive sources. The location of such a source is not well constrained and both the sub-continental lithosphere as well as the lower mantle have been suggested.

Arguments for the continued existence of a primitive bulk silicate Earth component (BSE) have been made on the basis of He-isotope studies. $^4$He is produced by the radioactive decay of U and Th isotopes, and, because the degassing of He from the mantle is a unidirectional process, high $^3$He/$^4$He ratios are interpreted as documenting the existence of undegassed, "primitive" mantle containing primordial $^3$He. MORBs are generated from a depleted and therefore outgassed mantle, and have relatively low $^3$He/$^4$He ratios (although they still contain a significant amount of $^3$He).

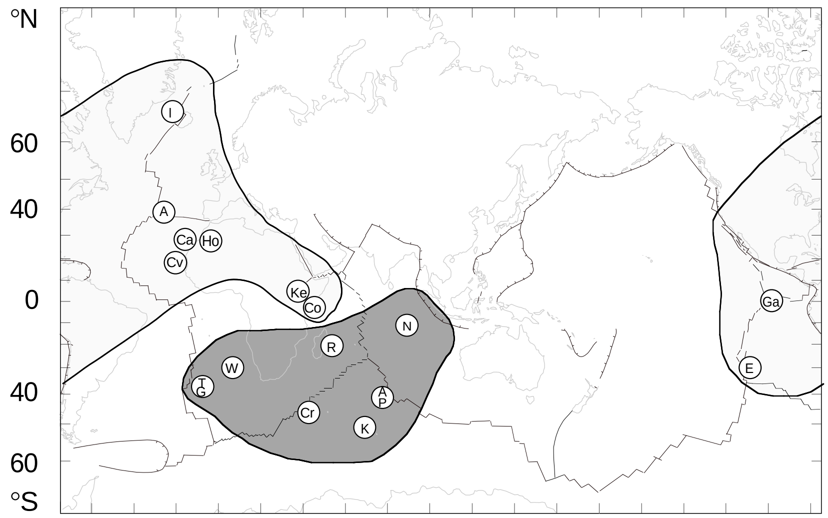



Figure 3.4.10-2: Large geographical domains with similar isotopic characteristics. Hotspot or ocean island basalts locations are: I, Iceland; A, Azores; H, Hoggar; Ca, Canaries; Cv, Cape Verde; F, Fernando de Noronha; Ga, Galapagos; E, Easter Island; Co, Comoros; T, Tristan da Cunha; G, Gough; W, Walvis Ridge; Cr, Crozet; R, Réunion; K, Kerguelen; A, Amsterdam; P, St. Paul; N, Ninetyeast Ridge; Ke, Kenya.

OIBs with high $^3He/^4He$ ratios (up to 4 times greater then MORB) are thought to come from this undegassed or primitive mantle.

The interpretation of the He-isotope data is hampered, however, by the fact that $^3He/^4He$ is not simply correlated with any of the heavy radiogenic isotope ratios. That is, high $^3He/^4He$ values occur in OIB with "depleted" Sr, Nd and Pb signatures, whereas samples with BSE-like Sr, Nd and Pb often have very low $^3He/^4He$ ratios. It has also been recognized that high $^3He/^4He$ mantle can be formed by incomplete degassing and trapping of He to form gas-rich zones in the mantle with low U/He ratios. If this happens early in the earth's history those gas-rich zones could potentially survive with very high $^3He/^4He$ ratios and serve as present day OIB sources. It has also been proposed recently that $^3He$ comes from interplanetary dust grains that are carried into the mantle with subducted oceanic sediments.

Perhaps the strongest argument for the existence of at least small amounts of undifferentiated mantle comes from a small number of peridotites that show major element, trace element and some isotopic characteristics that are almost identical to best estimates for the BSE. The occurrence of these peridotites is extremely rare however; only 3 or 4 are known. Furthermore, their chemical characteristics could conceivably be explained by more complicated modes of origin.

*The enriched mantle (EM) source:* The presently most favored generic model for enriched mantle reservoirs involves subduction and recycling of continental material. This works especially well for the so-called EMII source, since its isotopic characteristics are similar to continentally-derived sediment. Mixing arrays between the depleted MORB source or bulk Earth and sediment are clearly consistent with the sense of curvature noted for the EMII mixing arrays. Interdisciplinary studies directed at determining the origin of EMII sources should be able to address a number of interesting questions relevant to the history of the deep Earth.

*St. Helena or HIMU reservoir:* A less abundant OIB type is one indicating involvement of a reservoir with a high $^{238}U/^{204}Pb$ ratio (= "$\mu$ ", hence "HIMU") for which the type locality is St. Helena. A variety of origins have been proposed for this source, ranging from (*i*) extraction of Pb into the core; (*ii*) recycling of ancient altered oceanic crust to recycling of ancient continental crust; and (*iii*) intra-mantle metasomatism.

The HIMU component falls well to the right of the geochron in a $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram. It follows that the HIMU U/Pb fractionation must be substantially younger than core formation since core formation was completed early in Earth history. Thus extraction of Pb to the core during core formation is not a likely cause of the HIMU signature in certain OIBs. One possibility is extraction of Pb into the core during long term chemical and physical interactions between the core and mantle, which could serve to develop a HIMU component in a core/mantle boundary layer (CMBL). Core-mantle interaction with Pb partitioning into the core is, however, not favored because it appears that U enrichment, not Pb depletion, is characteristic of HIMU. Arguments against core extraction based on siderophile and chalcophile element abundances in oceanic basalts (Ba/W, Pr/Mo and Ce/Pb ratios) are also convincing.

The composition of altered oceanic crust does not support derivation of HIMU directly from such material. However, oceanic crust is modified by the subduction process. In particular, the process of dehydration during transformation into eclogite, can lead to changes in the final recycled ocean crust which approximate the requirements for the HIMU source. Recycled continental crust and/or sediment, however, clearly are not suitable as sources for HIMU.

Identifications of HIMU with metasomatic processes have been based on a putative mixing relationship between HIMU and EMI in the isotopic data. It has been suggested that EMI and HIMU may be complementary parts of the same metasomatic process (infiltrate versus residue). In summary, the origin of the HIMU source remains an open question which an interdisciplinary study may be able to address.

#### 3.4.11 Mixing and homogenization

An important source of information about the Earth's mantle is the body of geochemical and isotopic data obtained from mantle-derived rocks, specifically mid-ocean ridge basalts and ocean island basalts. These observations give some indication of the size and duration of mantle heterogeneities. Geochemical observations of surface rocks provide an intriguing map-view of the surface expression of underlying mantle heterogeneity, but they do not independently provide strong constraints on the location or history of mantle heterogeneities (Figure 3.4.10-2). Clearly convection plays a lead role in the evolution of mantle heterogeneities. The plate tectonic cycle continually introduces new heterogeneities into the mantle by melting and subduction, and other sources of heterogeneity (such as delamination of the continental lithosphere) have been proposed. At the same time, mantle convection destroys heterogeneities by convective mixing. To understand the relative rates of formation and destruction of heterogeneities in the mantle, it is essential to to understand mixing by convection. In recent years, new numerical and laboratory approaches have been developed to model mixing and stirring in flows.

The oceanic data set for Sr-Nd-Pb isotope variations suggest that the four components may be adequate to describe the isotopic data; depleted MORB mantle, a HIMU source characterized by high $^{206}Pb/^{204}Pb$ and low $^{87}Sr/^{86}Sr$, an of enriched mantle component (EMII) and one (EMI) close to the estimated bulk silicate Earth (BSE) or the primitive mantle. One of the most interesting observations is that the global distribution of these four isotopic components is far from random.

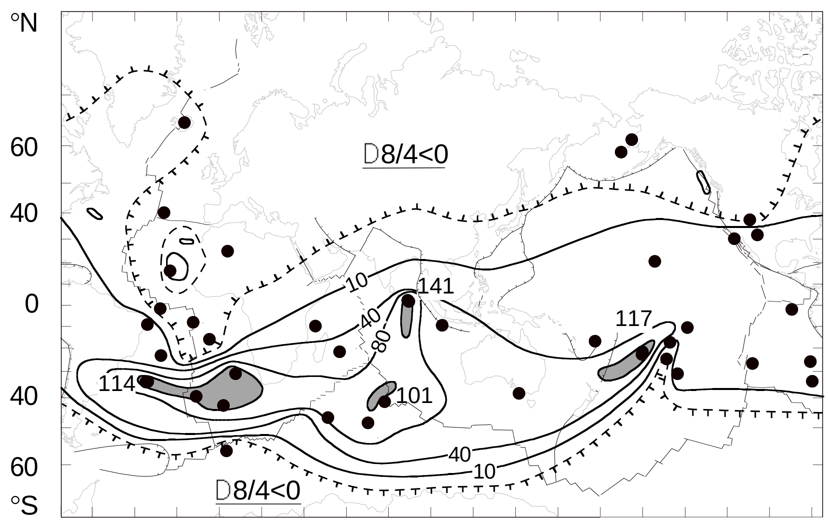



Figure 3.4.11-1: World maps showing distribution of the DUPAL isotopic province based on lead isotopic data and contouring.

The enriched mantle components are restricted to the southern hemisphere in a belt between the equator and 50° S (and define the "DUPAL anomaly").

The DUPAL anomaly is the most prominent example of the existence of large-scale heterogeneity (Figure 3.4.11-1). This globe-encircling feature, centered on southern latitudes, documents heterogeneity on the scale of thousands of km that took more than $10^9$ years to develop. Many present-day oceanic hotspots also occur within these latitudes, suggesting a possible causal relationship between the mantle source materials, enriched in K, U and Th, and the heat production associated with plume generation. Ocean islands within this belt tend to include the most extreme examples of each of the recognized isotopic endmembers. Such large-scale heterogeneities may reflect the non-uniform distribution of subduction over the surface of the earth at any given time. Portions of the mantle (e.g., the segment that once lay beneath the former southern-hemisphere super-continent, Pangea) might be more enriched in recycled material, which in time would lead to distinctive isotopic signatures. The correlation of the surface expression of geochemical and isotopic heterogeneity with the geometry of past subduction regimes is an intriguing subject for future interdisciplinary research.

Substantial correlations exist between the Pb, Nd and Sr isotopic tracers. If the large scale features of isotope arrays are created by mixing of separate mantle reservoirs and not by mixing of melts, then these hold great potential for understanding the location and evolution of these components. One mixing array appear to result from mixing of EMI and HIMU mantle components. Another array which appears to be well defined is an array stretching between DM and HIMU.

It would appear that the depleted MORB source and HIMU components are located in the mantle in contiguous geometry, such that their mixing can precede mixing with the enriched mantle. As for arrays involving EMII, what is remarkable about the "EMII anchored" arrays is their large range and approximate collinearity. None of the other three components serve as staring points for arrays which traverse such a large range in Sr and Nd. Thus, EMII contrasts significantly from the other components in that it tends always to mix toward some intermediate composition in Nd-Sr-Pb isotopic space.

The isotopic and chemical heterogeneity of the MORB-source reservoir is an important issue, because it can be used to tie together geochemical results with numerical experiments on mantle convection. A remarkable feature of the Earth's upper mantle is the extreme uniformity of mid-ocean ridge basalts. One view is that convection is an efficient blender and that the MORB source is a rather thoroughly homogenized region of the mantle (as evidenced by so–called $N$-type MORBs). However, weak heterogeneities at all length scales in mid-ocean ridge basalts (MORB) indicate some diversity in the source region. Weak heterogeneities may reflect the presence of incompletely mixed subducted material which "contaminates" the MORB isotope signature. Mid-ocean ridge and oceanic island basalts have systematic worldwide variations in Sr and Pb isotopes. Another view is that convective mixing need not be very efficient. Such evidence comes primarily from the large isotopic and chemical heterogeneity in OIBs, including maps of the so–called DUPAL anomaly. The "DUPAL anomaly" represents mantle heterogeneity on the scale of thousands of km that took more than $10^9$ years to develop. Several possible origins for the DUPAL anomaly have been proposed. If the pattern of mantle convection is predominately layered, injection of material from the lower mantle may create variations in OIB isotope signatures. Global scale spatial variations in the injection rate would lead to variations in the MORB and OIB signatures. Alternatively, the global variations may result from variability in the isotopic character of blobs within the mantle. Whether the mantle convects in one or several layers, variations in the amount and types of subducted material could lead to global variations in the mantle signatures. Subduction is in general not uniformly distributed over the surface of the Earth; thus subducted material is currently being introduced unevenly into the mantle. The correlation of geochemical/isotopic heterogeneity scales with the geometry of past subduction regimes is an intriguing subject for future interdisciplinary research.

The observations on MORBs indicate that compatible and moderately incompatible elements are comparatively uniform in their concentrations, while some (but not all) highly incompatible elements show relatively heterogeneous distributions. This is consistent with theories of highly efficient mixing in the mantle, but is insufficient to demonstrate it. Such homogenization appear to predate the development of the present day heterogeneities in OIB sources. The view of the upper mantle that emerges from these considerations is that convection has erased most of the heterogeneities left in the residual mantle region when the main mass of the continental crust was formed. The heterogeneities in the present day source regions of MORB and OIB are only 1 to 1.5 Ga old. Their chemistry is consistent with differentiation caused by magmatic processes observed in present-day MORB as well as hydrothermal alteration of MORB and recycled continental crustal material. This process still continues on a large scale, and mantle convection has not erased these secondary heterogeneities.

Models of the origin of the above-mentioned isotopic characteristics must preserve the distinct sources of the heterogeneities from one another for long periods of time while the isotope signatures develop. At the same time, a nearly homogeneous region must develop to provide a source for MORB. In the mantle this may be accomplished by physically isolating different reservoirs from one another, as, for instance, if the mantle is convectively and compositionally layered. Numerical calculations showing that thermal convection rapidly smooths out heterogeneities tend to favor such a model (Figure 3.4.11-2). However, to date no numerical calculation has taken into account all aspects of the problem. The strongly depth–dependent and nonlinear rheology of the mantle may prevent convection from smoothing out all heterogeneities, so that that some old material persists for a long time in the form of 'blobs'.

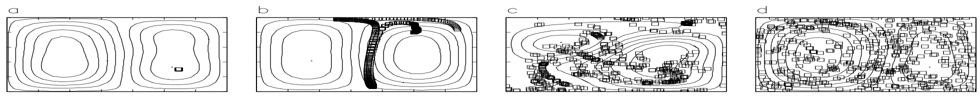



Figure 3.4.11-2: Convective mixing in a chaotic flow. A cluster of passive tracers was placed in a box undergoing chaotic Benard convection. Instantaneous streamlines display "snapshots" of the flow. The complex "marble-cake" structure that develops after about 6 overturns (c) may represent the source of weak heterogeneities in MORB at all length scales. After 9 overturns (d) the fluid is nearly homogeneous.

An accurate estimate of the efficiency of mixing in the mantle is necessary to interpret the geochemical observations. This requires development of numerical models of convective mixing in three dimensions with realistic material properties, including temperature, depth, and stress dependent viscosity and variations in the bulk composition of the mantle.

### 3.4.12 Chemical and isotope reservoirs

How many discrete mantle domains exist? Where are they located. How do they form? Geochemical data help to constrain the sizes of identifiable reservoirs within the framework of models of layered or whole-mantle circulation. They identify some of the sources of the circulating heterogeneities as being of mainly crustal and/or lithospheric derivation, but they do not decisively distinguish between different types of circulation. Geochemical data also does not uniquely identify the location of the various isotopic reservoirs/components that have been recognized.

*Depleted MORB mantle source reservoir (DM):* The mass balance between crust, depleted mantle and undepleted mantle, based on Nd and Sr isotopic evidence as well as trace element abundance patterns, suggest that about 30% of the mantle is depleted and balances the enrichments in the total mass of the continental crust. This mass balance obviously reflects only the actual proportions of the reservoirs if there are no additional unidentified reservoirs. It is clear that DM is located in the "upper" mantle, however, arguments still exist as to whether this means the upper 650 km or 1000 km.

*OIB source reservoirs:* Evidence on the nature and mean ages of different source reservoirs comes from the geochemical fingerprints of MORBs and OIBs. Consideration of several isotopic variations in certain OIB and continental flood basalts (CFBs) indicate that they may be partly derived from a relatively undepleted portion of the mantle. This has provided geochemical evidence for a two-layer model consisting of an upper depleted and a lower undepleted or primitive layer. However, much recent isotopic and trace element evidence suggest that most or all OIB source reservoirs are definitely not primitive, although some appear to be derived from slightly modified primitive mantle. Models consistent with the OIB evidence typically invoke recycling of oceanic crust and lithosphere or subcontinental lithosphere. Such recycling is a natural consequence of mantle convection.

Overall, the results are consistent with but do not prove a layered mantle where the upper layer contains both MORB and OIB sources, and the lower, primitive mantle is not sampled by present-day volcanism, with the possible exception of continental flood basalts. The final understanding of where the oceanic mantle components come from and how they move about and interact will depend on integrating all of the geochemical data with high resolution seismic tomography.

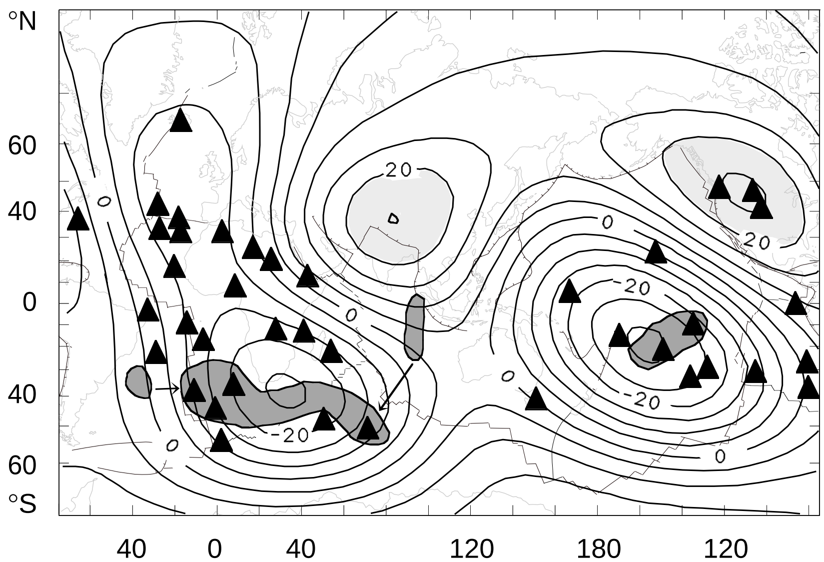



Figure 3.4.12-1: World maps showing contours (in m/s) of seismic velocities in the lower mantle from seismic tomography, the locations of hot–spots (triangles), and the DUPAL anomaly maximum in the Indian–South Atlantic and Central Pacific regions (hatched areas). Note the correlation between the DUPAL anomaly and the seismic velocity minimum, and that most hot–spots are above the low velocity regions.

*Primitive (or close to) undifferentiated mantle reservoir:* The source of some CFBs as well as the EMI source appear to be reservoirs with close to bulk silicate Earth composition. They need to be stored out of the upper mantle circulation for a long time. This can be done in the subcontinental lithosphere or in the lower mantle. A subcontinental lithospheric source is likely since this is clearly capable of long-term storage. However, the lower mantle appears to not be totally degassed (as evidenced from $^4He/^3He$ ratios, which indicate that primordial helium is still present in the Earth) and is an alternative site for these reservoirs.

*Subcontinental lithosphere source(s)*: The subcontinental lithosphere along with MORB, are the only mantle reservoirs whose locations are clearly identified. The components identified in OIBs sources also appear to have been identified in continental basalts that are likely to have been derived from the subcontinental lithosphere. Thus the whole range of oceanic Sr-Nd and Pb isotopic variations can be reconciled by delamination of continental lithosphere. Entrainment of such material in the upper depleted mantle circulation provides all the necessary OIB components; their survival time need not be long, because aged subcontinental lithosphere is always available.

*Enriched mantle reservoir (EMII):* The isotopic data do not support an old mean age for this reservoir so old sub-continental lithosphere, a lower mantle or core/mantle boundary layer all seem unlikely. Short-term storage in a mesosphere boundary layer (MBL) is one possibility that has been suggested. Perhaps more likely is that this reservoir exist as heterogeneities within the depleted upper mantle due to recycling of sediments in subduction zones.

*The HIMU reservoir:* As discussed earlier, it is possible that HIMU is metasomatic in origin and is stored in the core/mantle boundary layer (CMBL). A subcontinental lithospheric source is also possible since the metasomatic imprint of the HIMU source is consistent with abundant trace element and isotopic evidence for metasomatized xenoliths from the subcontinental lithosphere.

Many important questions concerning the origins and locations of isotopically distinct mantle materials remain to be answered satisfactorily. Nevertheless, mantle isotopic taxonomy has given us much of the foundation on which current ideas concerning the chemical structure of the mantle are built. Work in this field has given rise to the now conventional wisdom that recycling plays a critical role in determining the chemical character of the mantle. Although the distribution of hotspots at the surface of the earth is clearly limiting, much remains to be learned through systematic isotopic and geochemical characterization of important centers of ocean island volcanism. New results must be interpreted in the context of evolving petrological models for mantle melting, and geophysical models of plume dynamics and mantle convection. The rate of future gain from these endeavors can be accelerated by carefully planned collaboration between, and coordination among, investigators in these fields.

#### 3.4.13 Global climatic changes induced by deep processes

An important link between interior processes and surface conditions comes from the recognition that tectonics, in particular, mountain building, has a major effect on global climate. A systematic cooling of the surface (air and ocean) temperature over the past 30 Myr can be directly ascribed to the uplift of the Tibetan Plateau, the most significant topographic feature on land. With this cooling, estimated to have amounted to $\sim$10 °C, there has been a world-wide increase in glaciation over the past 3 Myr. Ironically, there is a "chicken-and-egg" effect as well, in that cooling can produce increased erosion, and therefore enhanced uplift (due to isostatic response) and topographic relief. In addition, the episodic rise and fall of sea levels is strongly influenced by dynamic motions in the deep Earth. Changes in spreading rate along with motion of continents on a surface with dynamic topography contribute to the complex geological history of all plate margins. Unraveling the history of the geological environments requires an understanding of the deep Earth motions.

The oceans and atmosphere, which are known to have been outgassed from the mantle early in Earth history, have continuously been affected by subsequent deep processes. It is now clear that considerable amounts of water are recycled into the mantle at subduction zones, where it can be stably locked up at depth within dense, hydroxide minerals. It therefore appears that several oceans' worth of water has been circulated into the mantle and, in fact, the primary reservoir of water for the Earth may well be at depth: the mantle may contain tens to hundreds of times the amount of water present in the "hydrosphere" (oceans and atmosphere) at the surface.

It has also long been recognized that volcanic eruptions affect climate (*viz.* the relatively cold summer immediately after the 1815 Tambora explosion), and the more recent examples of El Chichon and Mount Pinatubo show how relatively small and therefore potentially frequent eruptions can have dramatic consequences. In these cases, the trace quantities of sulfur extracted by the magmas from the mantle had, upon eruption high into the atmosphere, a disproportionately large effect on climate. What, then, are we to make of the recent evidence for "superplumes", indications of eruptions orders of magnitude more extensive that seem to have occurred $\sim$100 Myr ago? Understanding these exhalations from the deep interior will impact our knowledge of atmospheric evolution and possible major environmental upheaval.

A manifestation of global climate and temperature change that is of particular short term importance is changes in sea level. Changes in the mean temperature of the ocean can cause noticeable changes in global sea level. More dramatic are changes that would result from melting of the Antarctic or Greenland ice sheets. The measurement of sealevel changes is complicated by the

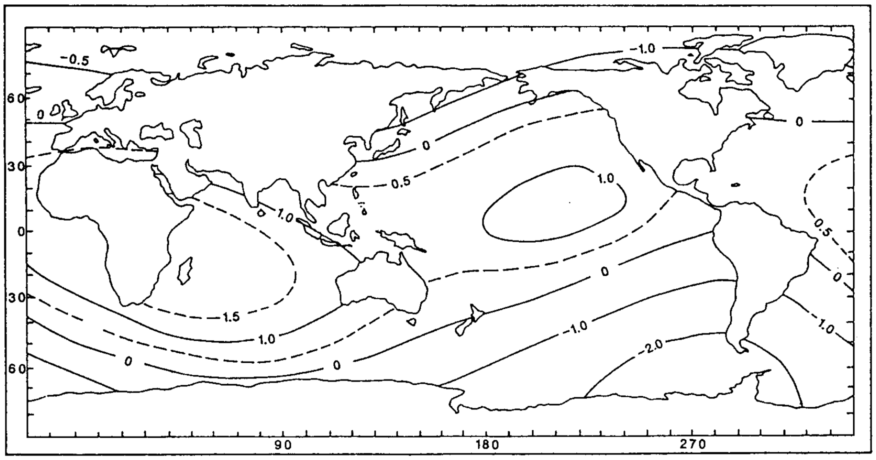



Figure 3.4.13-1: Global observed sea level change after the effects of mountain glacier melting and glacial rebound have been removed. Contours are in units of mm/year, and the corrections are of the order of 0.5 mm/year.

effects of post–glacial rebound that is still occurring at a slow rate following the disappearance of the Pleistocene ice sheets 15000 years ago. (*cf.* Figure 3.4.7-2) The spatial distribution and magnitude of the effect depends on the rheology of the mantle as well as the history of the melting of the ice sheets. Measurements of sea level from historical tide gauges can be corrected for the effect, however the corrections are of the same magnitude as the signal (Figure 3.4.7-2). Thus reliable models of the effect require sound models of the response of the Earth's interior to the changing loads on the surface. These models frequently rely on a range of other observations, such as the motion of tectonic plates and other longer term phenomena. This illustrates the nature of understanding the behavior of the whole Earth system, and the need for the integration of studies across a wide range of disciplines in order to solve current problems of the Earth's behavior and possible trends in the near future.

# 4 A Program for Studies of the Earth's Deep Interior

## 4.1 Introduction

The program we propose for research on the Earth's deep interior is aimed at a number of scientific problems that are of pressing scientific interest, yet are difficult to approach under the current arrangements. These are problems that by their nature require a larger and more sustained effort than is represented by a principal investigator and his or her immediate research group, that require some support of facilities that goes beyond that possible under individual grants, or that require a multidisciplinary or interinstitutional effort among different groups. These criteria are different, but sometimes overlap, and some examples may help to illuminate them.

The question of the vertical scale of mantle convection is a problem addressed by seismologists, geodynamicists, geochemists, mineral physicists and other earth scientists, and it is certainly one of the central problems in understanding the dynamics and evolution of the Earth's interior. A program that would bring together investigators from a number of relevant disciplines and promote their cooperation and interaction on this question may well be the best way of overcoming the current lack of progress on this outstanding problem.

There are other examples of this type that we discuss below. For each of these **Cooperative Research Projects** a concerted, cooperative and interdisciplinary approach is very likely to lead to significant advances. What is needed is a program to bring about and support the sort of effort that is needed.

The other type of problem is exemplified by the development of models, such as seismic models of the Earth's interior structure or large numerical models of flow and convection in the Earth's interior. The development of such models requires expertise and effort that frequently goes beyond that available from a single group. Yet such models are essential for a range of investigations in Earth science, and must be available to the wider community. A program that would facilitate cooperative efforts to develop and maintain such models is needed for advances on a spectrum of problems.

This type of problem we refer to as "Development of infrastructure", and we discuss several examples further below.

## 4.2 COOPERATIVE RESEARCH PROJECTS

### 4.2.1 Subduction zones and slabs

Subduction is one of the most observable of large-scale mantle dynamic processes. There are strong topographic and gravitational features associated with the density anomalies in downwelling regions, while island arc volcanism provides geochemical tracers of melting processes associated with downwelling materials. Slabs are seismically "visible" via both their earthquake activity and generally high seismic velocities, consequences of the extreme thermal conditions in subduction zones. Yet geophysical investigations have not achieved a quantification of slab composition and dynamics, including fundamental issues such as the maximum depth of penetration of subducting lithosphere, which is critical to resolving the dynamic configuration of the mantle. While progress has been substantial in each of the separate disciplines that can 'sense' the downwelling lithosphere, it is clear that resolution of the basic outstanding questions about slabs will require a coordinated, multi-disciplinary attack on the problem.

This will include the development of self-consistent petrological/phase equilibria models for the subducting lithosphere with their associated seismic and gravitational properties. Resolution of the role of kinetically suppressed, metastable phase transitions and the mechanism of deep earthquakes is closely intertwined with efforts to seismically image the internal velocity structure of deep slabs, and coordinated interdisciplinary efforts are critical for testing and resolving various hypotheses relevant to the chemistry and thermal state of deep slabs. This is an area where coordinated research thrusts are particularly ripe for rapid progress, provided additional support is forthcoming for the necessary substantial collaborative efforts.

### 4.2.2 Core–mantle interactions

The core-mantle boundary is perhaps the most intriguing region within the Earth's deep interior: the changes in material properties across the boundary are as great as those that take place at the Earth's surface. Although far less is known about the core-mantle boundary than more accessible regions of the Earth, recent years have seen an explosion of new results. Perhaps the most important has been the recognition of the importance of interactions at the core-mantle boundary between the core and the mantle, and that understanding these interactions is a critical ingredient of understanding how the Earth works.

Further progress in understanding these interactions, which are dynamical, thermal, electromagnetic and chemical in nature, requires research in many areas, and must be built on a collaborative effort between workers in different disciplines, including: high-pressure experiments to determine the phase equilibria, kinetics and transport properties of the mixtures expected at or adjacent to the core-mantle boundary; seismological studies to characterize the nature of the lowermost mantle, uppermost core and the topographic relief in between; geomagnetic studies to map the magnetic field at the core-mantle boundary and the fluid flow at the core surface; geodetic studies of changes in the Earth's rotation; and the synthesizing effort of fluid dynamicists to establish the connections between these results.

Part of the excitement in this research thrust is the difficulty in reconciling the inferences from these many different areas of research: such reconciliation will come only from collaborative investigations, and should lead to a major advance in our understanding of the dynamical processes that control the structure and evolution of the Earth's deep interior.

### 4.2.3 Geochemical reservoirs

Using isotopic indicators, geochemists have identified a number of mantle reservoirs, presumed to be source regions of varying history and depth. The interpretation of these putative reservoirs lags behind the data collection and is a major problem, requiring a collaborative approach among all parts of the earth sciences community. Several needs are evident, including (a) a far better understanding of what happens during and after partial melting of a source region, (b) a sustained quantitative assessment of large-scale mantle mixing for a variety of geophysically constrained models, (c) experimental measurement of partition coefficients and transport properties under conditions relevant to the mantle (including high pressures), and (d) a more systematic collection of relevant geochemical data with more complete areal and temporal coverage (the latter being needed to discern possible variations of geochemical patterns over geological or shorter times for a given source such as a hot spot). Data collection on natural samples would be greatly aided by input from theoretical workers, identifying the critical geochemical parameters or data sets that would be useful in constraining physical models. An example of a well-focussed and timely thrust in this area would be a collaborative effort which integrated large-scale fluid dynamical modelling of the mantle, with experimental and theoretical work on what happens in the partially molten region and during magma delivery, with the aim of explaining both the relatively homogeneous isotopic systematics of MORB and the relatively diverse ("multi-reservoir") character of OIBs.

### 4.2.4 Mantle transition zone

Largely because of a lack of appropriate mineral-physics data and detailed knowledge of the thermal regime of the mantle, controversy exists as to whether all of the changes in seismic velocities and density observed within the transition zone of the mantle (between 400 and 800 km depth) are solely the result of iso-compositional phase changes of the minerals or whether changes in chemistry also exist between the upper and lower mantle. High-pressure petrologists have produced detailed knowledge of phase boundaries of major mantle minerals in terms of the relevant thermodynamic variables: pressure, temperature and composition and mineral physicists have determined the room- or low-pressure seismic velocities of most high-pressure phases (or their crystal-chemical analogs synthesized and measured in the laboratory), but knowledge of the effect of the combination of the high pressures and temperatures of the transition zone is less complete. In principle, sufficient data could be obtained to construct complete density and seismic-velocity models as functions of thermal regime of the Earth.

Although previous research has related radially averaged earth models to compositional, phase assemblage and thermal models of the mantle, three-dimensional versions of such models have yet to be created. Such models are a necessary preliminary to understanding the Earth's mantle as a dynamic system. These models will incorporate seismic maps of velocity and density with models of thermal and material transport as well as geoid data. Specifically we need global maps of the precise depth of the principal seismic-velocity increases of the transition region (e.g., those roughly at depth of 400 and 650 km). A considerable body of data needs to be collected on the effects of high pressure and temperature on the seismic velocities and densities of the minerals of the transition region. Large high-quality sets of global seismic data can now be recorded and archived. These data need to be inverted to obtain three-dimensional maps of the transition region. The major facilities in high-pressure petrology and mineral physics need to be harnessed to produce the data to interpret global maps of the transition region in terms of thermal regime, phase assemblages and composition.

### 4.2.5 Mantle plumes

Mantle plumes have for some time been invoked to explain intraplate volcanism, particularly hotspot tracks such as the Hawaiian-Emperor chain. The initial stages of plume activity result in catastrophic volcanic events, such as the Deccan Traps flood basalt, which often precede continental breakup and episodes of rapid plate motions. These events may also cause severe environmental disruption (e.g., $CO_2$ outgassing) and lead to mass extinctions. This new "plume" tectonics requires a first-order modification (or addition) to plate tectonics as a dynamical theory. Unlike plate tectonics, the current plume paradigm does not offer well-quantified explanations for the observed phenomena; although plumes are widely thought to result from boundary-layer instability at the core-mantle boundary (CMB), they could also arise from sources within the mantle. It is difficult to explain the fixity of hotspots relative to plate motions in a convecting mantle. Plume melting beneath the lithosphere and plume volcanism (the main thing we observe at the surface) are poorly understood and only weakly integrated with laboratory and numerical models for 'solid-state' mantle plumes. Seismic imaging provides evidence for plumes beneath hotspots only to about 200 km depth, with no direct evidence of any connection with the CMB. The large number of 'distinct' geochemical sources needed to explain plume isotopic and trace element signatures defies simple explanations in terms of conduits tapping isolated mantle reservoirs.

Development of a successful theory of 'plume' volcanism (hotspot tracks, continental flood basalts, oceanic plateaus) requires interdisciplinary research bearing on all chemical and physical processes occurring between the core and the crust. Geochronological and geochemical studies of hotspot tracks as well as seismic imaging of the mantle beneath active hotspots must be directed toward quantified testable hypotheses based upon dynamical models of plumes. Accordingly, dynamical models must become more sophisticated in addressing processes of melting as well as interactions with the source (CMB) and sink (lithosphere) boundary layers, e.g., plate tectonics and heat transfer from the core (the geodynamo). As with modern efforts to model plate motions, we need to develop sufficiently powerful, well-documented and accurate 3-D numerical modelling codes – a goal well within reach of current computer technology which has not been achieved by individual geophysical investigators. We also need well-chosen integrated petrological, geochemical, seismological and geodynamical studies of purported mantle plumes (e.g., Hawaii, Iceland, Yellowstone) in order to meaningfully constrain the models.

### 4.2.6 Core surface flows

Although the Earth's fluid outer core is inaccessible to direct measurement, the secular variation of the geomagnetic field, which occurs on timescales as short as a decade, allows us to map the pattern of fluid flow immediately beneath the core-mantle boundary. In effect, we are able to see the pattern of convection at the core surface.

Mapping this flow pattern is not straightforward, and involves problems of data analysis and interpretation, the reliable extrapolation of the geomagnetic field from Earth's surface to the core surface. Furthermore, acceptable maps of the flow must be dynamically plausible: at this time, three dynamical constraints have been proposed, the toroidal flow hypothesis, the assumption of tangential geostrophy, and the steady flow hypothesis, but none is clearly favored. Ultimately, the geomagnetic data will tell the conditions and extent of the validity of these hypotheses, resulting in valuable information about the state of the Earth near the core-mantle interface.

Although the primary motivation for mapping the flow is to yield constraints on the geodynamo operating in the core, mapping the core flow is important to a number of investigations. It may even prove possible to deduce from the flow where the hot spots at the base of the mantle are situated. Variations in electrical conductivity in the deep mantle, and particularly within the D" layer, resulting from chemical reactions between the core and mantle which affect the extrapolation of the magnetic field to the core surface, may also be elucidated from such investigations. Of geomagnetic interest, issues such as how well the frozen flux hypothesis works, and also at what time and space scales the diffusion of toroidal flux from the core into the mantle is important, can be addressed.

An important connection between the apparently disparate fields of geomagnetism, seismology and global geodesy exists in that the correlation of geomagnetic secular features with seismically determined core-mantle boundary topography provides a prediction of the torque acting between mantle and core producing an observable change in the length of day. A major goal of the initiative is to foster interconnections such as this between diverse disciplines.

#### 4.2.7 Effects of deep Earth processes on the Earth's surface

Deep seated convection in the Earth's interior ultimately drives surface tectonics and determines the long term evolution of the Earth. The deep interior is also a source of materials which make up the crust, atmosphere and hydrosphere. Consequently an understanding of the nature and history of convective motions in the mantle is necessary if we are to determine how, when and where the continents originated and were assembled. More immediate questions relate to the time-variability of internal convection, including the effect on plate motions and geometry, and the associated processes at ridges and subduction zones, and on the geoid, surface topography, sea-level changes, post–glacial rebound, and regressions and transgressions of sedimentation at continental margins. Hot spots and associated flood basalts are further examples of deep seated processes with important effects on the surface. Where do plumes originate, and what is the origin of material that eventually erupts on the surface? Is the development of plumes related to larger scale convection in the deep earth or is it relatively independent? Do plumes, or superplumes, significantly affect plate motions? What is the flux of volatiles carried to the surface by plumes (as well as by subduction related volcanism, mid-ocean ridge and ocean island volcanism, and kimberlites and related rocks. What are the possible sizes and locations of reservoirs for volatiles in the deep interior?

To address these questions, several things are needed. Global seismic models of mantle structure that are more detailed than current ones are needed. Models of the rheologic structure of the mantle are also needed. The history of plate configurations and motions over the last few hundred million years is also needed, as well as the history of hot–spots and flood basalts. In addition, the global distribution of current vertical and horizontal deformation fields, including post–glacial rebound, are needed. To tie all these together requires the development of realistic spherical convection codes with the capability of including lithospheric plates and small scale instabilities related to plume development. The work involved in addressing the questions above is highly interdisciplinary, and would require collaboration of workers in global and regional seismology, geodesy, the geologic history of plate tectonics and volcanism, and modellers of convection and flow. Bringing such a group together is difficult under the current programmatic structure, and the total project would severely tax the funds of a single program. Nevertheless, the problems are extremely important for understanding the longer term history and dynamics of the Earth.

### 4.3 DEVELOPMENT OF EARTH MODELS

#### 4.3.1 Introduction

In addition to specific research thrusts, there are some long-term research endeavors, in the areas of seismic tomography, mantle convection and the geodynamo, here grouped together as 'scientific infrastructure', which are deemed necessary for the successful synthesis of observation, experiment and theory into a comprehensive model of the Earth's interior. Each of these endeavors is a large-scale computational effort, similar to the general circulation model of atmospheric dynamics, to produce large trustworthy numerical codes which serve both to synthesize current knowledge and to provide a mechanism for testing new hypotheses. These computational activities, described in the following paragraphs, will be of continuing interest and concern under the initiative.

### 4.3.2 Seismic earth models

The propagation characteristics of seismic waves are the most sensitive indicators of three-dimensional (3-D) inhomogeneities in deep-earth structure. From the spatial variations in seismic wave speed and attenuation factors, geophysicists seek to deduce the internal variations of temperature and composition and thus place constraints on the dynamical mechanisms operating within the mantle and core. The process of using observations of seismic waves — their travel times, dispersion and attenuation characteristics — to derive a model of earth structure is an inverse problem. Before an inverse problem can be posed, it is first necessary to solve the forward problem: given an earth model, compute the wavefield observables. Algorithms have been developed to numerically synthesize complete seismograms from 3-D earth models, and inversion procedures based on these algorithms have been applied to large sets of seismograms recorded by the global networks of digital stations. These efforts and related studies have, over the last decade, produced a first generation of 3–D earth models.

The resolving power of current models is limited to features with horizontal scale lengths greater than a few thousand kilometers and wavespeed variations on the order of 1%. This is not sufficient to differentiate among the competing hypotheses about the style of mantle convection; in particular, the models are not yet been able to settle a forty-year-long controversy regarding the magnitude of the vertical convective flux between the upper and lower mantle, or to resolve the more recent issue of the existence of a chemical boundary layer just above the core-mantle interface. There is a critical need, therefore, to move forward on two fronts. First, refinement of the global models must continue by incorporating additional information on the seismogram. Most of the wavefield motion recorded at periods greater than 20 seconds is potentially interpretable in terms of deterministic earth structure, but only a small fraction of the available information is currently exploited; the rest is treated as 'signal-generated noise'.

To access these new types of information and use them to refine existing earth models is a formidable project requiring the development of new forward–modelling and inverse–modelling procedures, the manipulation of very large data sets, and the systematic assessment of how this new information actually improves the resolving power of the earth models. Seismic models of the Earth's elastic and anelastic properties must be tested against independent constraints, such as those provided by global geodetic observations. The magnitude of this task has outstripped the capabilities of a single research group working at a single institution. A carefully coordinated, sustained effort will be required, and we believe this can best be accomplished by the mechanisms of the CSEDI program outlined in this document.

The second front for future research is the development of regionalized images of earth structure that are consistent with, but more detailed than, existing global models. An example would be the western Pacific, where the seismicity is high, the data coverage is excellent, and high-resolution imaging of the subduction process can be used to assess the nature of downward flow through the mid-mantle transition zone. Another example might be at the base of the mantle, in the D" region, where improved resolution can be obtained from signals strongly reflected and refracted by the core–mantle boundary. Such specialized studies might best be undertaken in the context of coordinated, multi-institutional projects that address the regional problems from a multi-disciplinary point of view. It will be necessary, however, to coordinate these efforts with those directed at improving the global models.

### 4.3.3 Development of mantle convection, flow and general circulation models

Convection is the dynamic process that has governed the evolution and history of the Earth, and which currently drives the surface tectonics and associated processes. Knowledge of the convective flow in the Earth is necessary for a wide range of investigations of global dynamics. Studies of large scale processes, such as the transport of material through the mantle from subduction zones to ridges or global plate motions, require a global, large-scale convection model. Yet many of the processes, such as those associated with the formation and assimilation of the lithosphere require the ability to resolve length scales of some tens of kilometers. These simultaneous requirements are difficult to satisfy, even on the largest computers; the problem is exacerbated if the time evolution of the system must be followed. An additional difficulty is the extreme variation of mechanical properties between the lithosphere and more deformable mantle, and that the heterogeneity of properties occurs over small length scales. The inclusion of the creation and transport of partial melt is perhaps even more difficult; nevertheless ascent of melt at mid–ocean ridges is the dominant process by which heat is transported from the Earth's interior to the surface.

These requirements of a large scale convection model for the Earth's interior illustrate some of the difficulties. Production of a code that would meet all requirements is beyond our current capability, yet some sort of capability is needed for a wide range of problems. It is likely that some processes may be usefully parameterized, and their effects approximated. Different algorithms may be more useful than others, depending on the problem of interest. The development of a suite of useful convection and flow models is clearly beyond the capabilities of any one group (even those at national laboratories), and requires the cooperation and collaboration of many workers, ranging from geoscientists with insights about various processes and problems to numerical analysts with knowledge of state-of-the-art algorithms. The effort would be ongoing as advances in computers and algorithms were made, and it would be essential to produce numerical models that were usable by the community for a range of problems, having adequate documentation and debugging. The effort should also include the testing and comparison of different algorithms and models in order to illuminate shortcomings and to verify the accuracy and usefulness of the models.

A related part of the modelling requirement is the need for the geologic boundary conditions that may be needed for some problems. Tracing the circulation of material in the mantle over geologic time requires the history of plate configurations and motions to be known in sufficient detail and form be applied as a boundary condition. The assembly (as well as the determination) of such information is itself a significant, and ongoing, task that should be integrated with the production of models.

What is needed for this problem is support for a collaborative effort to develop convection and flow codes applicable to a spherical earth with lithospheric plates. Processes that are likely to be important, and which should be included in one form or another, include compositionally driven flow, solid state phase transitions, partial melting, melt transport and differentiation. The models should include the capability of tracing material transport and mixing. Different codes and algorithms should be compared, and their applicability to different problems or processes assessed. The codes should be developed so that they can be widely used within the community, at supercomputer centers as well as on modern workstations where appropriate. The result should be a set of numerical models that researchers could use to address a range of global problems.

The availability of such models would open up a range of problems to attack by the community who are knowledgeable about the problems but who currently lack the numerical tools to attack them. It would eliminate the inefficiency of the repeated development of numerical models, and the more serious inefficiency of the use of inadequately tested and verified models. This would undoubtedly lead to significant advances in our understanding of the large scale dynamics of the Earth's interior, and its interaction with a wide range of processes on the Earth's surface.

### 4.3.4 Geodynamo models

An elusive goal of geophysics for many decades has been to understand the process by which the Earth generates its magnetic field. Recently, several groups (notably in the United Kingdom and Germany, but also in the United States and Japan) have constructed three-dimensional numerical dynamo models, and there is now, for the first time, a reasonable expectation that a major advance in our understanding of the geodynamo will be forthcoming in the foreseeable future.

But modeling the geodynamo is an extremely complicated procedure: a systematic collaboration between these various groups, particularly in the area of verification of results and to decide on the most promising approach to geophysically realistic solutions, including the role of compositional buoyancy in the driving mechanism, will soon be required. And fundamental aspects of the physics of the dynamo still require resolution: although it is now generally agreed that the geodynamo operates in a strong magnetic field regime (i.e. one in which magnetic and rotational forces are comparable in strength), there is still no consensus on whether that regime is of model-Z type (in which core-mantle coupling controls the core flow) or whether it is of Taylor type (in which core-mantle coupling has only a secondary role to play). The resolution of this dilemma, which is necessary for further progress to be made, would form a suitable research thrust in the near future.

Another topic that has come increasingly to the fore very recently has been the way that the lateral inhomogeneities of the D" layer alter the core flow, particularly immediately below the mantle, and therefore also influence the magnetic field reaching Earth's surface. This is a step towards a long-term goal of understanding the dynamics of the core-mantle system as a whole. It is also close to observation and is less formidable than the full geodynamo problem; it is therefore particularly attractive as a short-term geomagnetic research thrust.

# 5 Operation and Management

The goal of the science plan is to accelerate progress toward an understanding of how the dynamics of Earth's deep interior controls its structure and evolution on: to understand complex dynamical processes, such as the generation of the Earth's magnetic field, the relation of its present state to its history, and the nature of the engine in the deep interior that drives plate tectonics at the surface. There are two principal, complementary components to the science plan: a proposed NSF program, Cooperative Studies of the Earth's Deep Interior (CSEDI) and a community based Coordinating Committee; the NSF program would evaluate proposals and support projects, and the committee would provide coordination within the community, among projects and with the NSF.

## 5.1 The NSF CSEDI program

The primary function of the NSF CSEDI program is to evaluate and provide support for cooperative studies focussed on fundamental problems of the Earth's deep interior. These new funds will be distributed by NSF using the usual mechanisms of peer review and panel evaluation of proposals. The proposal process will be open to all investigators who wish to submit proposals, but proposal ranking may take into consideration several criteria related to the multi-disciplinary, multi-institutional aspects of the CSEDI program. These criteria are:

- A proposal should demonstrate the possibility of making accelerated progress on major problems of global significance;
- The proposed work should draw from, contribute to, or be aimed at establishing more than a narrow disciplinary perspective;
- A proposal should involve investigators from different research units.

The success of the proposed science plan depends strongly on the level of funding of the CSEDI program. If the program is funded at the expense of the traditional small grants program, the science plan will almost certainly fail. It is envisaged that in steady state the program might support 4 or 5 Cooperative Research Projects of several years' duration plus the continuing infrastructure programs. Using a rough figure of $300k to $400k per project results in a projected level of total support of $3 to $4 M per year. The CSEDI program is expected to ramp up to its steady level of funding over a few years. Proposals submitted to the CSEDI program might be reviewed by a separate panel, perhaps with coordination with the normal review process of the disciplinary programs.

## 5.2 The Coordinating Committee

The Coordinating Committee will consist of several (10–15) scientists representing the disciplines of geochemistry, geomagnetism, geodynamics, mineral physics and seismology, plus the chairman of the AGU SEI committee serving in an ex officio capacity. Each regular member would serve a three-year term, with staggered terms. Members should serve no more than two consecutive three-year terms. Officers, chosen from among the regular members, will include a chairman and a secretary.

This committee will be responsible for

1. organizing or coordinating topical symposia and other activities related to the CSEDI project;
2. promoting consensus within the US SEDI community on important problems of highest priority for focussed effort, and assisting in the resolution of controversies;
3. communicating this consensus to the larger community and governmental agencies;
4. disseminating discoveries and other results of the program as part of an educational outreach program.

These responsibilities are discussed in more detail below.

### 5.2.1 Relation to SEDI

The Coordinating Committee may serve as the US national SEDI committee. SEDI (Study of the Earth's Deep Interior) was chartered in 1987 as a Union Committee of the International Union of Geodesy and Geophysics to foster and facilitate cooperative studies of the structure, composition, energetics and dynamics of the Earth's deep interior, particularly the lower mantle, the core and the core-mantle boundary region.

The ultimate goal of SEDI is an enhanced understanding of the past evolution and current thermal, dynamical and chemical state of the Earth's deep interior and of the effect that the interior has on the structures and processes observed at the surface of the Earth. The success of SEDI has been due in large part to its timeliness, as the earth sciences appear poised to complete the plate-tectonic revolution begun more than 25 years ago.

SEDI encourages the formation of National Initiatives which are compatible with its objectives. Such initiatives have already been established in Canada (the Global Geodynamics Project), Japan (The Earth's Central Core Project) and the United Kingdom (the Geodynamo Project). CSEDI would constitute a US national SEDI Initiative.

The American Geophysical Union has established the Studies of the Earth's Interior Committee (SEI), which is charged with promoting and coordinating SEDI-related activities within the AGU. In order to ensure coordination of the proposed science plan with AGU activities, the chairman of the SEI Committee, who is appointed by the President of AGU, will be an ex officio member of the Coordinating Committee.

### 5.2.2 Relation to Agencies

The Coordinating Committee will provide a liaison between the US national SEDI community and the funding agencies, to help ensure (a) that appropriate funding is provided for targeted Cooperative Research Projects and infrastructure projects while not adversely affecting individual research projects and (b) that multi-disciplinary, multi-institutional projects are not neglected because of non-overlapping administrative mandates. If necessary, the Coordinating Committee could provide periodic written or oral reports of activities within the scientific community to appropriate funding agencies.

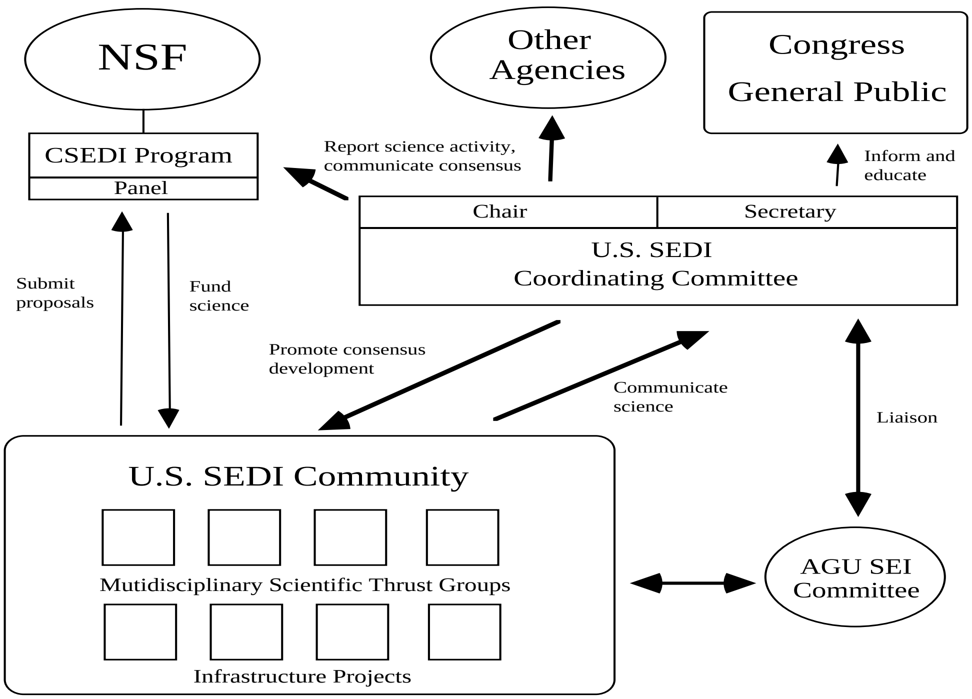



Figure 5.2.0-1: An illustration of the various components of a CSEDI program, and their interactions.

### 5.2.3 Support and Financing

Activities of the Coordinating Committee, such as organizing topical conferences, maintaining liaison with the community, and disseminating results to the larger community will require some modest support. The administration of the different cooperative research projects would be undertaken by those participating in the project. In this way administrative burdens would be widely shared, and their expenses minimized.

### 5.2.4 Establishment

The initial Coordinating Committee was chosen at a public meeting held 11–12 September, 1992 at MIT in order to discuss the draft of the Science Plan for the CSEDI program, and other related matters. For further information, contact Prof. Thomas H. Jordan, Rm. 54–920, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA 02139.

## 5.3 Operations and activities

### 5.3.1 Topical Symposia

The Coordinating Committee will oversee the organization of topical symposia on subjects of particular interest to the SEDI community. Typically the symposia will be convened by an ad hoc committee, with some support and coordination from the Coordinating Committee.

The principal goal of these symposia will be to catalyze the interaction of different disciplines, and to precipitate a collaborative, coordinated effort to attack problems of pressing importance in understanding the Earth's deep interior.

The meetings will also acquaint scientists interested in submitting proposals to the CSEDI program with the relevant knowledge and problems in related disciplines, so that they may ultimately produce cooperative proposals of improved quality. An important product of the symposia should be a consensus about both the state of current knowledge about a potential research thrust and the areas which appear ripe for accelerated progress. These symposia will be distinct from those more narrowly focussed workshops which would be conducted by PIs during the course of their funded research grants.

Symposia topics will be chosen by the Committee from a list proposed by individual scientists, groups of scientists, or agencies. The sequencing of symposia topics will *de facto* set research priorities by catalyzing the submission of superior proposals to NSF and other funding agencies.

The Coordinating Committee will arrange publication of the results of these topical symposia in the peer-reviewed literature. The Committee will also encourage the symposia organizers to make available to a wider audience the information, such as graphics and videos, which results from the symposia. This may be done through existing AGU programs, such as the pre-college education program.

### 5.3.2 Infrastructure Oversight

The infrastructure projects are distinguished from the research thrusts by their longer duration, their possibly different structure (*e.g.*, having several complementary or supplementary projects active at any one time) and their long-term utility to the wider SEDI community. Consequently, the Coordinating Committee could be available to provide oversight of these projects to ensure that (1) adequate communication links are maintained between related projects and with the wider community, (2) efficient use is made of the funds provided by the CSEDI program, (3) any numerical codes produced are adequately verified, and (4) codes and data produced under the project are adequately made available to the SEDI community at the appropriate time. Other oversite mechanisms might also be proposed by the PIs of infrastructure projects.

### 5.3.3 Education and Outreach

An important part of the activity of the Coordinating Committee will be a sustained effort of education and outreach. This will begin with the topical symposia, which are aimed at education of geoscientists themselves, including graduate students. The published proceedings of the symposia will complement this effort toward peer education. However, we also strive to establish an active program to strengthen the link between fundamental academic research related to the deep Earth and college and pre-college education. Since geophysics deals with the planet we live on, it should as few other sciences be able to appeal to the student's and the general public's curiosity, love of learning and need to improve the understanding of our habitat. Despite this, geophysicists often fail where astronomers or space scientists succeed in attracting extensive public attention for their scientific endeavors. Improving this situation is not only in our own interest, it helps fill an education and information need that extends far beyond that of academia into industry, local and national government and society at large.

To strengthen the link with college education, the Coordinating Committee will promote the publication of tutorial papers on CSEDI research, both as introductions to the proceedings of symposia and in review journals. Projects may request extra funding to allow undergraduates to participate in the research, or to disseminate educational material to the undergraduate and pre-college student populations, and to science teachers at the high-school and middle-school levels, preferably in coordination with the appropriate educational programs of AGU, GSA etc.

The broadest level of outreach is the publicizing of discoveries and important results in the popular press, which will be encouraged and arranged by the Coordinating Committee.

# 6 Figure References

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# Contributors to Science Plan

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