CSEDI

2004

Cooperative Studies of the Earth's Deep Interior

- DEVELOPMENTS
- DISCOVERIES
- FUTURE

This document is the outcome of the CSEDI Workshop conducted on February 22-23, 2004 in La Jolla, California. It has been prepared by a Coordination Committtee that organized the workshop and was charged with summarizing its results in the present report. Many members of the research community contributed both to the workshop and to this document, but responsibility for the conclusions and any possible errors lies with the CSEDI Coordination Committee.

This report, and other information, is available at: **www.csedi.org**

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Summary

The first decade of NSF's **Cooperative Studies of Earth's Deep Interior (CSEDI)** Program has seen major discoveries about the structure and dynamics of our planet's mantle and core. Seismologists have imaged subducted slabs plunging toward the core, "superplumes" beneath Africa and the Pacific, ultralow-velocity patches at the core-mantle boundary, and unexpected structures at the center of the planet. Numerical models have shed new light on the origin and evolution of planetary magnetic fields, while advances in paleomagnetism reveal that the field has existed for billions of years and provide a record of its complex history. Technological advances in geochemistry document the origins and earliest evolution of the Earth, showing the wide range of sizes of heterogeneity in the mantle. Neutron and synchrotron beamlines now allow sophisticated measurements of material properties on samples held at high pressures and temperatures, characterizing for the first time the nature of these materials at deep-planetary conditions. Driven by advances in technology, observation and theory, the field is revealing major surprises about our planet's origin and evolution.

Much of this work has been done in a spirit of **multidisciplinary cooperation**, with developments in each field inspiring research in other areas. A new generation of scientists is thereby being prepared to address fundamental questions, using state-of-the-art technologies while maintaining a broad perspective on Earth's complex systems.

Gaining insight into the processes of Earth's deep interior provides **numerous benefits**. Public imagination is captured by the research, with discoveries inspiring coverage in major media, articles in popular science outlets, revisions in the way introductory science is taught, and even through fictional books and movies. Newly recognized links between Earth's interior and surface, raise questions such as: Is Earth's magnetic field collapsing and heading toward a reversal? How do processes in the mantle drive volcanic eruptions and contribute to climate change? And can studies of the behavior of natural materials at high pressures and temperatures lead to development of useful new materials?

Within the decade, the field is poised to make major advances in areas of significance to science and society. These realistically include a broad understanding of Earth's inner dynamics, incorporating core evolution, mantle convection, the driving forces of plate tectonics, and the interaction between the interior, oceans and atmosphere. CSEDI provides a framework for capitalizing on the new observational, experimental and theoretical advances made possible by the current development of major observational, experimental and computational facilities.

To maintain its success, the CSEDI program needs to provide support both for collaborative research and integrative activities, as these magnify the value of disciplinary and cross-cutting research conducted under other programs. The level of support required is an annual funding level of \$5 M (approximately 10 new projects per year supporting 2-5 PIs, ranging in size from \$200k to \$2M/project). Resources should also be allocated for larger projects and integrative activities as demonstrated by successful peer reviewed proposals, suggesting a program with a full portfolio growing up to \$10 M over the next decade.

Cooperative Studies of Earth's Deep Interior

- Developments, Discoveries, Future

Studies of Earth's deep interior – the majority of the planet – provide the framework for understanding our World, its origin, evolution and ability to sustain humanity.

Research on the deep interior is inherently interdisciplinary, drawing on principles from physics, chemistry, mathematics, engineering and computer science to address the unique challenges associated with understanding the remote reaches of our planet. It addresses such questions as:

- *What are the global forces driving geological processes?*
- *How do processes in the deep Earth offer the mineral and other resources needed by modern society? How do these processes drive devastating events such as volcanic eruptions, earthquakes and other natural hazards?*
- *How have the oceans and atmosphere developed over geological time, and what can that information tell us about climate change?*
- *How was planet Earth put together, and how has it evolved?*

Public Imagination is captured by research on Earth's deep interior, with discoveries inspiring coverage in the major media, articles in popular science outlets, educational materials, and even science fiction books and movies. People are fascinated by questions such as: Is the Earth's magnetic field collapsing, heading toward a reversal? How do processes in the mantle drive volcanoes and earthquakes? Can studies of the behavior of natural materials at high pressures and temperatures lead to development of useful new materials? How can we see into Earth's deep interior?

A decade ago, the scientific community recognized that new methods and an interdisciplinary approach would yield new insight into the operation of our planet. A science plan for Cooperative Studies of the Earth's Deep Interior (CSEDI) was developed by the US Coordinating Committee for Studies of the Deep Interior (SEDI) in order to highlight major issues that involve understanding the bulk of the Earth's interior (SEDI, 1993). The CSEDI plan presented a framework within which to foster cross-disciplinary research that would transcend traditional intellectual and institutional divisions. The CSEDI initiative anticipated the formation of a community-based science organization and an associated NSF program. That program has proven highly successful!

More than 10 years later the CSEDI community has grown and has produced numerous exciting discoveries involving the dynamics of the Earth's interior, and the interplay between deep processes and the environment at the surface. The community effort has been supported through the creation of the NSF CSEDI program, begun in 1996, which has funded cross-disciplinary research on the Earth's interior.

The CSEDI Community is highly international and cuts across most of the disciplines of solid Earth sciences, including seismology, mineral physics, petrology, geochemistry, geodynamics, geodesy, geomagnetism and paleomagnetism. Numerous specialized sessions on Studies of Earth's Deep Interior (SEDI) are held at the annual meetings of the American Geophysical Union (Fall Meeting exceeding 10,000), and about half of the regular Gordon Research Conferences on solid Earth sciences are devoted to the deep interior. The international SEDI scientific organization hosts meetings every two years, primarily in North America and Europe. The mailing list of International SEDI meeting participants includes more than 500 names, with roughly 40% of these individuals listing U.S. universities and government labs as their primary affiliation.

Driven by these successes, by advances in technology, and by an interdisciplinary perspective, the field is poised for new discoveries. An NSF-sponsored **CSEDI Science Plan Workshop** held in February 2004 brought together deep-Earth researchers to update the CSEDI concept and identify future directions of research. From that workshop, this document has been developed within the framework of the National Academy of Sciences 2003 *Basic Research Opportunities in Earth Science* (*BROES*) Report, and the NSF *GEO-2000* Report. The *BROES* report highlighted "Studies of the Earth's deep interior" as one of six promising directions for research in the Earth Sciences. *BROES* suggested investigations targeting time-dependent fluxes of matter accompanying solid-state mantle convection, evolution of the core-mantle boundary, origin and evolution of Earth's geomagnetic field, and the origin and evolution of the inner core. *GEO-2000* similarly highlighted the need to better understand the dynamical evolution of the deep Earth and the interactions between the planetary interior and exterior, using high-resolution and long-wavelength seismic imaging, state-of-the-art paleomagnetic and geochemical methods, new experimental methods in mineral physics, and advanced theoretical models.

Broader connections to planetary science and astronomy have become essential, as we expand our search for habitable environments – the origin and potential expanse of life – in the Solar System and beyond (*BROES*). Indeed the habitability of our own planet is strongly influenced by exchanges of water and carbon between the surface and the interior, making deep-Earth research relevant for understanding changes in environmental conditions both in the geological past and in the future.

NSF is not alone in considering deep–Earth studies to be important. NASA's Solid Earth Science Working Group (SESWG) recently outlined a strategic plan entitled *Living on a Restless Planet*. Of the six major research questions discussed, two are especially relevant to CSEDI goals: (1) What are the dynamics of the mantle and crust and how does the Earth's surface respond? (2) What are the dynamics of the Earth's magnetic field and its interactions with the Earth system? SESWG recommends a comprehensive observational program that includes continuous satellite observations of both gravitational and magnetic fields as well as of surface deformation to help address these questions.

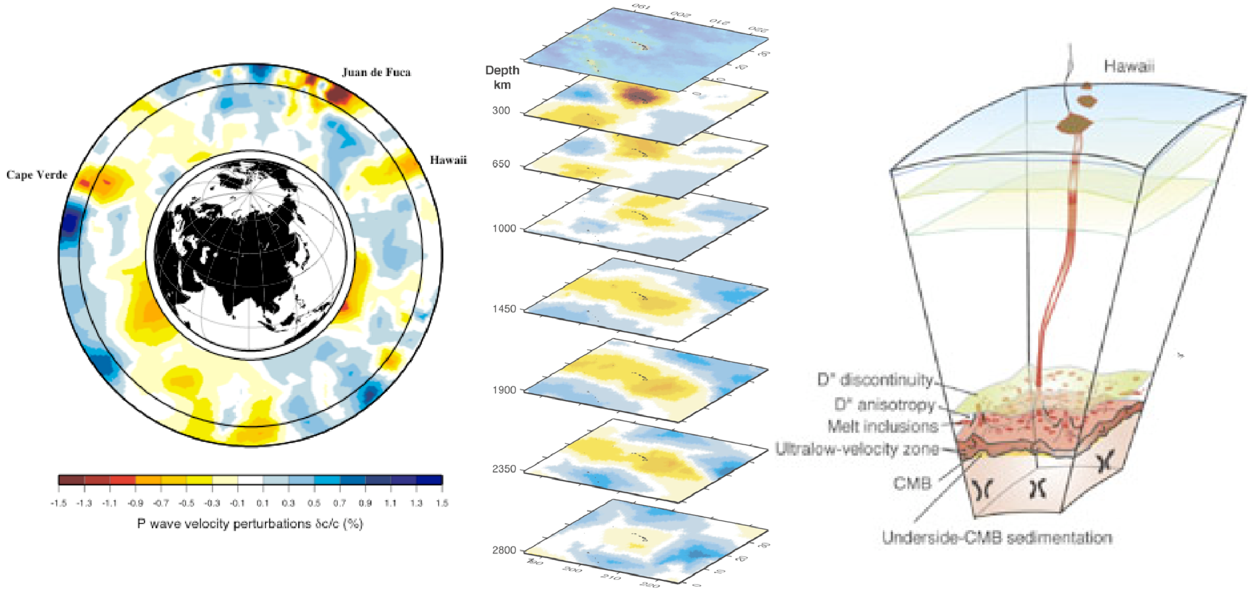
Facilities Used in CSEDI Research	**Community of Users**
GSN/PASSCAL broadband arrays Data Management Center	Seismology *Operated by IRIS*
National synchrotron facilities *National Synchrotron Light Source* *Advanced Photon Source* *Advanced Light Source*	Mineral Physics, COMPRES (NSF), GSECARS *Operated by DOE*
Neutron beamlines *Los Alamos Neutron Science Center* *Intense Pulsed Neutron Source* *Spallation Neutron Source*	Mineral Physics, COMPRES (NSF) *Operated by DOE*
National Supercomputing Centers *Pittsburgh, San Diego, NCSA*	Geodynamics, Geomagnetism *Operated by NSF*
USArray/Earthscope (*facility under development)*	Seismology, Geodynamics *NSF, NASA, USGS program*
Institute for Rock Magnetism U. Minnesota, Minneapolis	Paleomagnetism *NSF Multiuser Facility*

Accomplishments of the CSEDI Program

- Examples of major discoveries and insights

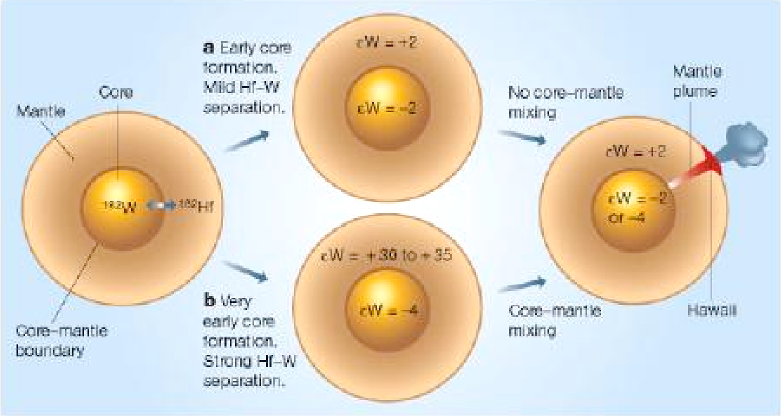
Dynamics of the Core-Mantle Boundary (CMB)

One of the most dynamic regions of the Earth's deep interior is the boundary between the liquid-metal core and rocky mantle, 2900 km beneath the surface. Changes in physical properties across this interface are even greater than those between the solid Earth and atmosphere.



Major Structures of Earth's mantle, such as the hot upwelling plume causing the Hawaiian volcanoes can be traced from the depths of the mantle to the surface by means of seismic tomography (left, center). The cross-section (right) schematically illustrates structures and processes at the core–mantle boundary based on seismic imaging, laboratory experiments and computer simulations. The D'' region at the base of the mantle may indicate regions where major plumes are created [R. Montelli, et al. (2004), Science; DePaolo, D. and Manga, M., (2003), Science; E. J. Garnero (2004), Science].

Seismological studies, combined with mineral physics and geodynamics, have revealed extreme lateral heterogeneity and other hints of intense physical and chemical processes across the CMB. Patches of ultralow seismic velocities at the base of the mantle suggest that extensive melting and chemical reaction are taking place between rock of the mantle and liquid metal of the core. Large structures deep beneath Africa and the south Pacific, revealed by seismic imaging, may be the source of major surface features such as hotspot volcanoes and elevated topography. The recent discovery of a high-pressure, post-perovskite phase opens new avenues of exploration for the core-mantle boundary. Identifying the role of deep-mantle processes in Earth's dynamical cycles remains one of the major open challenges of our field.



One promising approach for understanding chemical interactions at the base of the mantle attempts to distinguish chemical or isotopic signals unique to the outer core that would make it possible to identify samples at the surface that were once in direct contact with the core. Siderophile (iron-loving) elements and associated long- and short-lived isotope systems are among the best candidates as core signatures. Several isotopic systems have been proposed and developed in attempts to characterize metal–silicate interactions at the core–mantle boundary. Coupled enrichments in ^{187}Os and ^{186}Os (decay products of long-lived ^{187}Re and ^{190}Pt) consistent with elemental fractionations resulting from the crystallization of the inner core have been observed in some plume-derived lavas. If these isotopic signals were derived from the outer core, they may indicate that a substantial portion of the inner core crystallized within the first 2 Ga of Earth's formation. Two short-lived isotope systems, ^{107}Pd-^{107}Ag and ^{182}Hf-^{182}W have also been proposed as indicators of core-mantle interaction. The latter system, in particular, is of great interest because mass balance constraints require that the isotopic composition of tungsten in the core is substantially different from that of the silicate Earth. When fully developed, a combination of these geochemical tracers may ultimately confirm or deny mass exchange across the CMB [E. Hauri (2004), *Nature*].

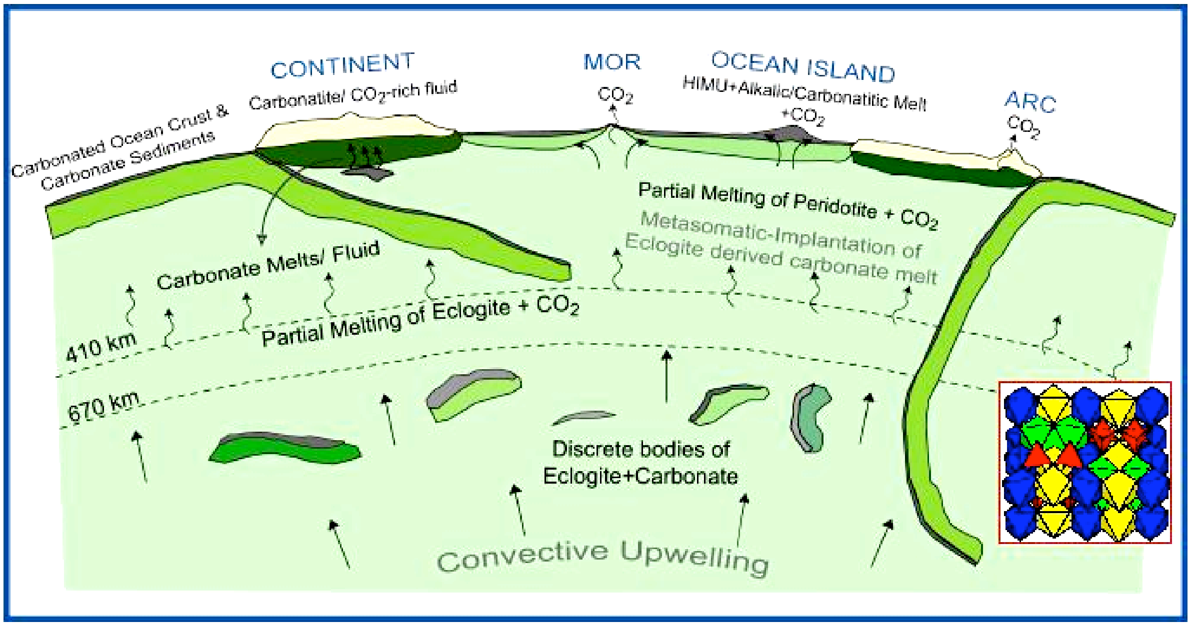
Role of Volatiles in Mantle Dynamics.

Volatile molecules such as water, carbon dioxide and methane are cycled into the Earth's mantle by subduction. The mantle is large, so it can potentially store vast quantities of these molecules and may therefore have played an important role in the geological evolution of the Earth's oceans, atmosphere and climate system.

Water has a direct influence on the Earth's internal dynamics because it can significantly alter the strength of minerals in the mantle. Variations in water content can produce very large changes in the effective viscosity of rock, strongly influencing the pattern of flow. Water may also weaken the lithosphere sufficiently to initiate new subduction zones, when convective instabilities develop at the top of the mantle. In the upper mantle, water can lubricate the base of plates, effectively decoupling their motion from the flow of the underlying mantle.

Water strongly affects seismic-wave velocities, so it can explain some of the observed heterogeneity of the mantle. It may even alter the way we interpret observations of seismic anisotropy for the history of flow in the mantle. Laboratory experiments suggest that the presence of water alters the plastic deformation of the upper-mantle rocks, producing different alignments of crystals when water is present or not. Increasingly, the presence of volatiles in the mantle is seen as an essential part of the dynamics of the interior.

It is known that water causes a dramatic reduction in the melting temperature of mineral assemblages in the mantle. Melting at subduction zones is commonly associated with dehydration reactions in the subducted slab that release water into the surrounding mantle. Water has also been proposed as a potential source of melting in the mantle transition zone, and possibly at the base of the mantle. Deep sources of melt can disturb the geochemical budget of the mantle in unexpected ways and contribute to the isotopic heterogeneity of trace elements that are brought to the surface by volcanism.



Cycling of volatile molecules through the Earth's mantle is known to have an important role in regulating the level of carbon dioxide in the atmosphere. Crystallographers have discovered that many high-pressure minerals, such as the wadsleyite form of olivine present in the transition zone, can contain large amounts of water as hydrogen dissolved into their crystal structures. Current research points to a large fraction of our planet's volatile budget is locked up inside the solid Earth. [R. Dasgupta and M. Hirschmann (2004)]

Understanding the Geodynamo

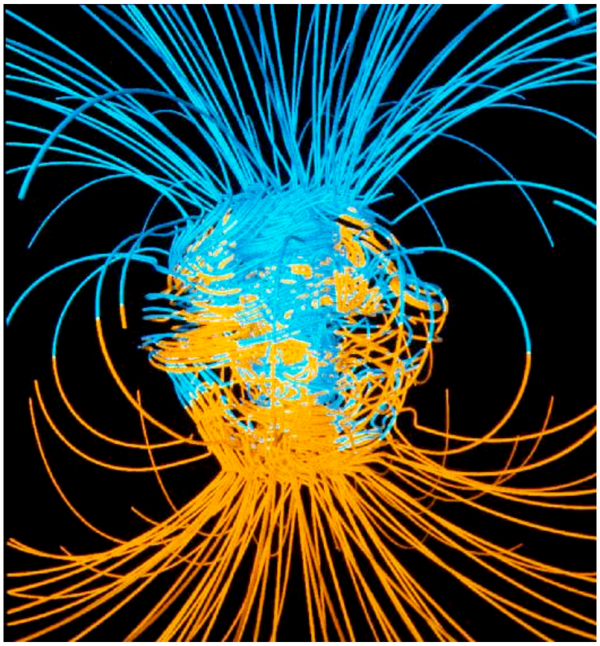
The origins and evolution of planetary magnetic fields offer some of the richest challenges in Earth and planetary sciences. In particular, the geomagnetic field offers the only direct geophysical observations about the past history of our planet, by way of the paleomagnetic record of field configurations and intensities recorded in rocks.

Advances in numerical methods and computing technology have led to dramatic advances in understanding how the Earth's magnetic field is sustained, and even exhibit reversals in polarity. Geodynamo models predicted rotation of the Earth's inner core, prompting new seismic studies aimed at documenting this rotation. At the same time, new geomagnetic and paleomagnetic databases are being developed that have led to a better understanding of the long-term evolution of the Earth's magnetic field from observations. Additional insights into the mechanisms of geomagnetism are obtained from laboratory models of the magnetic field using rotating magnetohydrodynamic devices.

Growing interest in geodynamo models has resulted in an explosion of new numerical models, each exploring a new modeling strategy or a different numerical technique. Encouragement is taken from the appearance of Earth-like features in the predicted magnetic field, even though the models are forced to adopt unrealistic values for several important properties of the core. These limitations are imposed by the spatial resolution of current numerical models, which is insufficient to capture the effects of small-scale turbulence. The problems are analogous to those facing global climate models.

Several schemes have been proposed to compensate for such limitations, and most studies introduce turbulent diffusivities of one form or another to deal with the effects of unresolved turbulence. Debate over the most appropriate strategy has highlighted the important fact that different choices yield different solutions. Yet we know that the persistence of the magnetic field in the geological record is a sensitive diagnostic for the evolution of the planet as a whole, and a better understanding of the physical processes that sustain the field are a prerequisite for interpreting this record.

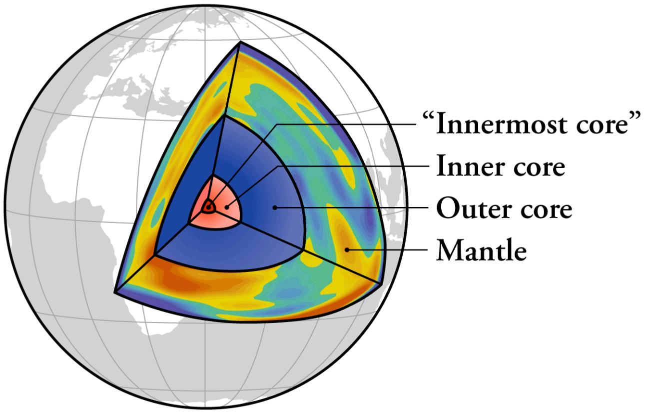
In order to make progress we need models that are capable of operating under Earth-like conditions. This goal will not be achieved with bigger and faster computers, at least in the foreseeable future, because a fully-resolved solution must account for fluid motion with scales ranging from 10^6 m down to 1 m or less. Instead, we need better schemes for dealing with the influence of small-scale turbulence on the large-scale flow and magnetic field.



Numerical geodynamo models have become an important new tool for investigating the dynamics and evolution of the Earth's core. Shown here are the magnetic field lines emanating from the Earth's core (spherical region in center) based on a modern dynamo calculation (*orange* and *blue* for south and north components, respectively). Progress in this area of research has motivated new lines of inquiry about the pattern of convection in the core, the motion of the solid inner core, field reversals, and possible interactions with circulation in the mantle [G. Glatzmaier and P. Roberts (1995), *Nature*].

The Inner Core

In the decade of the CSEDI program, a great deal has been learned about the Earth's solid inner core, a structure roughly 2/3 the size of the Moon that sits at the very center of our planet. Remarkably, the inner core is seismically anisotropic; measurements of anomalous splitting of the Earth's free oscillations suggest that the anisotropy must be dominantly axisymmetric, with the fast symmetry axis closely aligned with the rotation axis of the Earth. Early models of anisotropy in the inner core had a slightly tilted symmetry axis, and were used to infer a super-rotation of the inner core (with respect to the mantle) of about 1 degree per year using the temporal variation of the travel times of body waves which sample the upper part of the inner core. Subsequent modeling has shown that, locally, there is considerable heterogeneity in the anisotropy, and inferred super-rotation rates have now been significantly reduced. The anisotropy also has significant structure on large scales, with some studies finding hemispheric differences in the strength of anisotropy but with the uppermost part of the inner core being isotropic. The deepest part of the inner core (the bottom 300 km or so) may exhibit a conspicuously different orientation and strength of anisotropy.



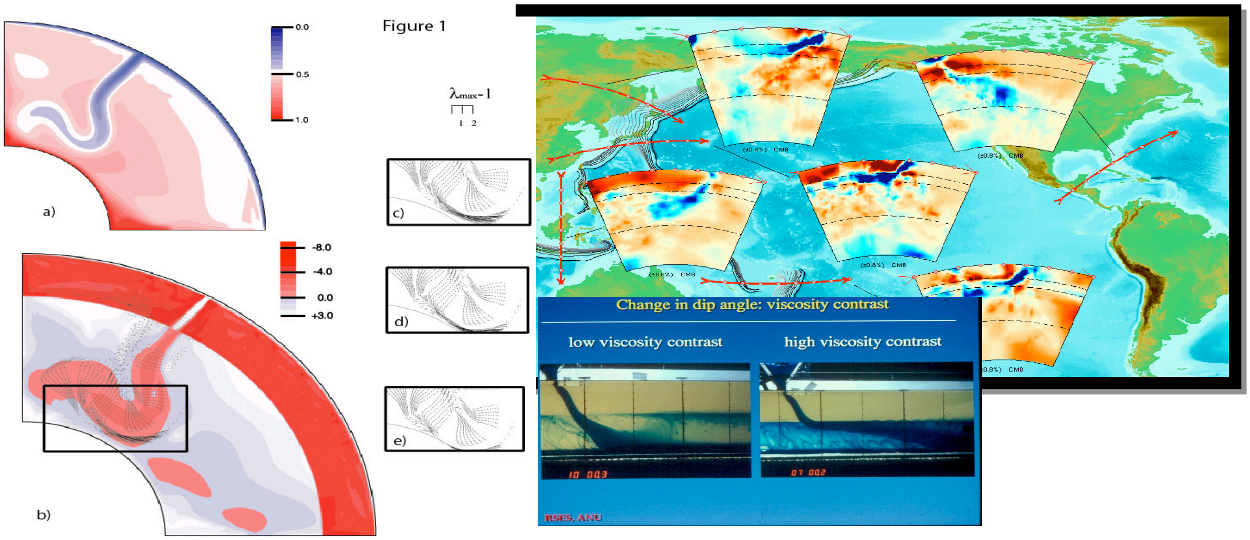
Complex seismological structure has led to the suggestion that the Pluto-sized inner core itself has an "innermost core" [M. Ishii and A. M. Dziewonski (2003), *Proc. National Acad. Sci.*]

Explaining these complex observations requires considering how the inner core has evolved with time. Current thinking is that, as the Earth cools, the inner core is slowly freezing from the outer core and grows with time. Some of the light impurities in the outer core are rejected at the freezing boundary, therefore giving a compositional change at the inner core boundary. These rejected impurities are gravitationally buoyant, and will drive flow in the outer core that can maintain dynamo action. Indeed, the conventional wisdom has been that the gravitational energy release from inner-core growth is essential to dynamo action. Some have even speculated that the reason Venus has no magnetic field is that it has no growing inner core. It is also possible that the presence of the inner core has a strong stabilizing effect on the magnetic field, since it imposes a diffusion time scale on the temporal variation of the field. Thus, while dynamo action may be possible without an inner core, the behavior of the field might be quite chaotic. The timing of inner core formation remains controversial, a topic that could be addressed by future geochemical and paleomagnetic observations.

How the conceptual model of the growth of the inner core relates to its complex anisotropic structure is still unknown. Indeed, we are not yet completely certain what crystal structure iron alloys have at inner-core pressures. Current experiments indicate that pure iron would almost certainly be in the hexagonal close-packed (epsilon) phase but, apparently, small amounts of alloying elements can stabilize other phases. Measurement of the elastic properties of iron alloys at extreme temperature and pressure is only now becoming possible, as are reliable "ab-initio" quantum mechanical calculations, so we can soon expect to have the information needed to quantitatively explore different models of structural growth.

Interaction of Subducted Slabs with Mantle Interfaces

For the past 30 years, there has been a vigorous debate about the depth extent of circulation in the mantle. Until recently, the preferred model of geochemists was a layered mantle with a relatively untapped (primordial) lower mantle. On the other hand, seismologists and mantle dynamicists generally preferred a model of whole-mantle circulation.



Numerical modeling of mantle dynamics (left) reveals the complexity of the deformation associated with subduction of slabs. Using high-resolution, time-dependent calculations with variable properties and deforming tracers makes it possible to estimate the origins and degree of anisotropy that should be expected in the lower mantle [McNamara et al., (2002) Nature]. Advances in numerical modeling methods and the increased availability of high performance computing have opened up new lines of inquiry into the dynamics of the mantle, and foster interdisciplinary studies to test the predictions made by numerical models. **Seismic tomography** reveals the fate of plate-tectonic slabs sinking into the mantle (characterized by blue colors, corresponding to fast wave velocities) at 5 subduction zones (along the transects marked by red lines). The deformation, and occasional stagnation of slabs as they pass through the mantle transition zone can be understood via **laboratory experiments** using fluids of variable viscosity [figure courtesy R. Van der Hilst (2004)].

As tomographic imaging of slabs in the mantle has improved, the picture that is emerging is consistent with neither of the above end-member models. Many slabs appear to be impeded by a barrier to flow at a depth of about 660km inside the Earth, and appear to "pond" at this depth. However, some slabs can be traced all the way to the core-mantle boundary. What emerges from the tomography is that the 660km discontinuity is not a major thermal boundary, in the sense that the top and the bottom of the mantle are, and that there must be significant mass transfer across this discontinuity. Of course, impediments to flow (such as a phase transformation and/or a viscosity increase) may make mass transfer across the 660 km discontinuity episodic (so-called “mantle avalanches”), leading to complexity in the seismic images of the lower mantle.

Reconciling the geochemical evidence for separate reservoirs within the Earth with the seismological evidence for slab penetration has become one of the central problems in deep-Earth science for the past several years. The ultimate resolution of this problem not only relies on improved seismological imaging, but also on more realistic dynamical modeling of the evolution of inhomogeneous systems and how they mix. Advances in computer modeling have led to a deeper understanding of the effects of rheology, slabs, and composition on mantle flow.

Emerging Inquiries

While interdisciplinary research has yielded many new insights, new questions have also opened up as a result of better observations and models. For example, seismic and geochemical measurements, combined with dynamical modeling, have created a greater appreciation of the complexity of the mantle beneath hotspots. The relatively simple models of a decade ago, involving a simple pipe-like plume originating from a deep boundary layer, have given way to more complex models, as the role of near-surface processes, including melting and continental rifting, are better understood. With the expected width of plumes being just at or below the threshold for detection by seismic means, the origin of hotspots remains one of the outstanding open questions about mantle dynamics. Likewise, combined seismic and mineral physics studies have revealed the likelihood of compositional heterogeneity in the deep mantle, but the interpretation of this heterogeneity remains enigmatic.

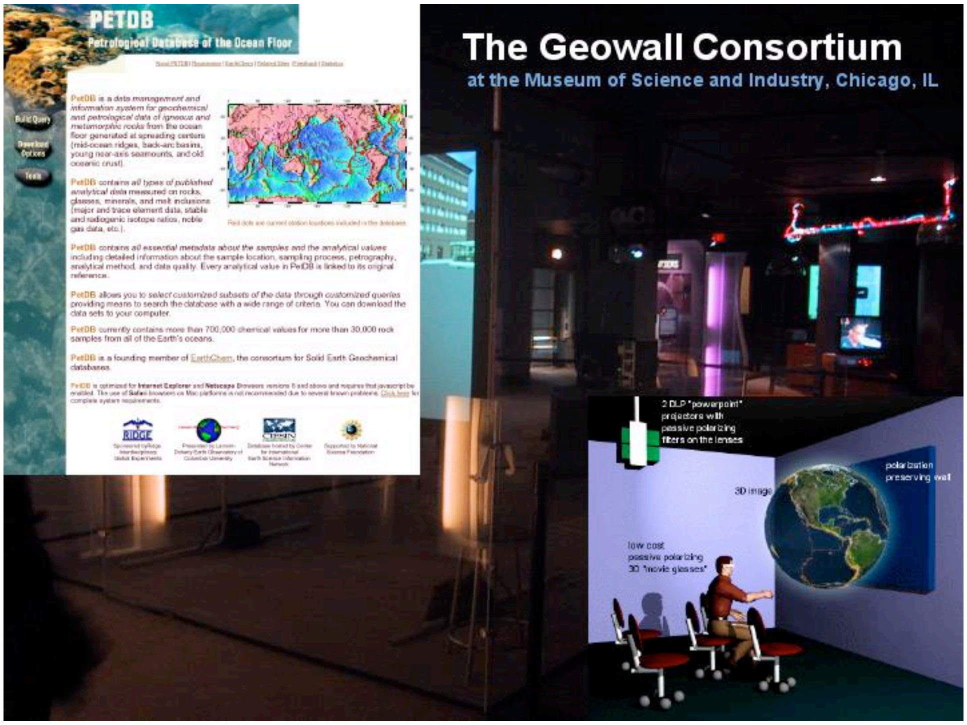
Wide-ranging impact across the sciences characterizes inner-Earth research, with applications extending to physics, chemistry and materials science, as well as across the full spectrum of Geosciences.

Broader Impacts of Deep-Earth Research

Computational Science, Information Technology and Mathematics

Geodynamics, seismology, geomagnetism and mineral physics rely heavily on computer modeling to deduce the Earth's internal dynamics. The magnitude of these calculations, the difficulty in characterizing the physical properties of the deep mantle and core, and the range of scales of space and time involved, make these applications of computer modeling especially challenging.

Progress continues to be made in collaborations between deep-Earth researchers and computational scientists, including close cooperation between scientists in universities and in the national labs. Recent efforts in this regard are the development of Geoframeworks and the Computational Infrastructure in Geodynamics (CIG) initiative, which are engineering new computational methods and making them widely available to the geodynamics community.



PETDB
Petrological Database of the Ocean Floor

PetDB is a data management and information system for geochemical and petrological data of igneous and metamorphic rocks from the ocean floor generated at spreading centers (mid-ocean ridges, back-arc basins, young near-axis seamounts, and old oceanic crust).

PetDB contains all types of published analytical data measured on rocks, glasses, minerals, and melt inclusions (major and trace element data, stable and radiogenic isotope ratios, noble gas data, etc.).

Red dots are current station locations included in the database.

PetDB contains all essential metadata about the samples and the analytical values including detailed information about the sample location, sampling process, petrography, analytical method, and data quality. Every analytical value in PetDB is linked to its original reference.

PetDB allows you to select customized subsets of the data through customized queries providing means to search the database with a wide range of criteria. You can download the data sets to your computer.

PetDB currently contains more than 700,000 chemical values for more than 30,000 rock samples from all of the Earth's oceans.

PetDB is a founding member of EarthChem, the consortium for Solid Earth Geochemical databases.

PetDB is optimized for Internet Explorer and Netscape Browsers versions 5 and above and requires that javascript be enabled. The use of Safari browsers on Mac platforms is not recommended due to several known problems. Click here for complete system requirements.

Sponsored by Ridge Interdisciplinary Global Experiments
Presented by Lamont-Doherty Earth Observatory of Columbia University
Database hosted by Center for International Earth Science Information Network
Supported by National Science Foundation

Examples of successful use of Information Technology include development of the Geowall (www.geowall.org) for visualizing complex data sets (inset at *lower right* illustrates 4-D imaging); data bases that provide direct access to chemical and isotopic data on modern and ancient lavas from numerous tectonic environments, and efforts such as Computational Infrastructure for Geodynamics (CIG) (www.geodynamics.org), which enables the deep-Earth community to take advantage of advances in computing technology by developing and maintaining software for computational geophysics. Databases offer researchers the cornerstone observations on compositional heterogeneities within the Earth. Together with the accompanying metadata, it is possible to develop temporal, spatial and compositional maps of volcanoes, hotspot trails, domains along mid-ocean ridges and the like, which are then incorporated into 3-D and 4-D models of flow in the mantle. Using the PetDB database as an example one can readily enter a query that provides a data file that can be viewed on the web or downloaded (petdb.ldeo.columbia.edu/petdb/). GERM (earthref.org/GERM/index.html) is an initiative that also addresses the concept of characterizing geochemical reservoirs in and on the Earth; such characterization includes physical, chemical and temporal aspects, as well as examining fluxes between reservoirs.

The NSF sponsored workshop on Frontiers in Mathematical Geosciences identified a need for new methods to characterize complexity at multiple scales as one of the challenges to understanding the solid Earth. The resulting Collaborations in Mathematical Geosciences program has funded cooperative research between mathematicians and geoscientists to model magnetohydrodynamics, develop new methods for seismic characterization of heterogeneity in the deep Earth, and develop new methods for modeling mantle dynamics. These computational efforts are completely in the spirit that has been established by the CSEDI community.

Data Integration

Over the past decade, several community-based initiatives have produced publicly accessible databases for geochemistry, paleomagnetism, seismology and mineral physicists. These databases allow the user to query vast datasets, and they vary widely in the level of scientific and computational sophistication required of the user. Increasingly these database resources are being used by a broad range of scientists to ask questions about the source regions within the mantle of many surface rocks, and the scales of compositional heterogeneities in the mantle. The diversity of databases and increasing breadth of scientific questions leads to the hosting of multidisciplinary databases under collective umbrellas: one example is provided by www.EarthRef.org, which collects geochemical, chronological, and magnetic information under broadly similar metadata structures.

Individual technologies continue to evolve to successively higher levels of sophistication, and the communication between disciplines becomes increasingly demanding, yet ever more critical. As the ability to compare – let alone unify – observations among many specialties becomes more challenging, it will be essential to provide an infrastructure that encourages interdisciplinary exchange of information so that scientists can begin to address such questions as: Why is the Earth as geologically active as it is?

Evolution of the Magnetic Field

At the very longest time scales the existence of a changing magnetic field can be linked to the evolution of the Earth itself, and its study is an important part of deep-Earth research. Yet it also provides a specific example of the interaction between deep-Earth research and other scientific disciplines, with particular relevance to societal needs.

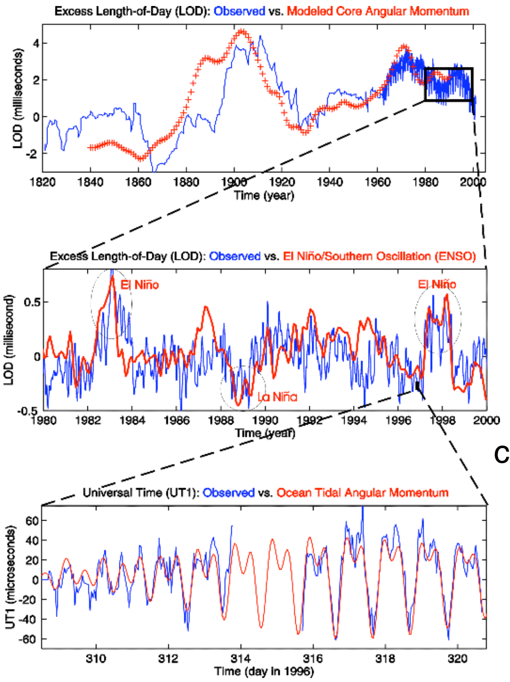
The Earth's magnetic field acts as a shield preventing the supersonic flow of charged particles in the solar wind from reaching Earth's lower atmosphere, thereby protecting the surface from damaging electromagnetic fluctuations. Even so, occasional solar storms have catastrophically shut down large parts of the North American electricity grid. Although the greatest part of the geomagnetic field derives from dynamo activity in Earth's liquid outer core, other physical processes also make important contributions. The time-varying external part of the field, is modulated by solar activity and by seasonal and diurnal cycles, and it directly affects Earth's electrodynamic environment, its thermospheric dynamics and possibly the evolution of the lower atmosphere. It also induces fields within the Earth, producing detectable signals related to global ocean circulation and induction in Earth's lithosphere and mantle.

The presence or absence of a magnetic field will influence the degree to which atmospheric erosion and sputtering occurs, and thus can have important long-term implications for atmospheric evolution. The combined strength of the solar wind and of the internal magnetic field influence production of cosmogenic isotopes in the upper atmosphere, including ^{14}C used for radiocarbon dating. Anomalies in past ^{14}C in turn provide evidence of long-term changes in Earth's climate, possibly as a consequence of changes in solar activity. Understanding geomagnetic field variations on both short and long timescales is thus necessary to understand solar–planetary relationships and long-term climate changes.

Short-term variations have a direct influence on society, because of the ever-increasing need to evaluate the impact of space weather on power supplies, communications and satellites. The expanding South Atlantic Magnetic Anomaly, due to the changing dynamo pattern in the core, has serious effects on degrading low-Earth orbiting satellites. The current decay of the Earth's magnetic dipole is largely due to changes in the field in that region. Geomagnetic field models and forecasting thus have important practical applications in the areas of space weather and radiation hazards.

Geodesy from the Earth's Interior to the Hydrosphere

Another example of the connection between research in Earth's interior and the atmospheric, ocean and hydrologic sciences emerges from space-based geodetic observations. Decadal fluctuations in the rate of rotation are thought to be a result of oscillations in the liquid iron core, but detection of these oscillations through precise measurement of subtle variations in the rotation rate also provide information about fluid motions in the atmosphere and oceans, which is of interest to researchers in atmospheric and ocean sciences. Changes in the direction of the Earth's rotation induced by tidal forces (known as nutations) provide information about the anelasticity of the mantle and the structure of the core-mantle boundary, while progress in our understanding of the Earth's interior has, in turn, facilitated better predictions of the Earth's nutations. Measurements from space of deformation of the Earth's surface, including GRACE, the GPS constellation, and InSAR, are starting to provide information about the rheology of the Earth's interior, but these measurements can only be interpreted in conjunction with a good understanding of long-term climatic change, because ice sheets are among the loads causing deformation on the Earth's surface.



Changes in Earth's rotation rate, shown as variations in the length of day (LOD) as a function of time, can be understood as a signal combining the effects of the outer core's dynamics (fluid flow and magnetic field generation) on time periods of centuries (*top*), climate change on periods of decades (*center*), and tidal forcing on periods of days. Observational measurements (*blue*) are compared against theoretical models (*red*) to demonstrate the level of current understanding of our planet's internal and surface dynamics, as well as to indicate aspects of the signal that require further study. The length of each day, a simple property of our planet, thus offers a rich array of information about forces in and on the Earth [B. Chao (2003), *EOS, Trans. AGU*].

A Planetary Perspective

CSEDI's contributions to understanding Earth's evolution directly impact the planetary sciences by helping to determine why the planets are so diverse. Why do some planetary bodies possess active magnetic dynamos, while some (like Mars) had dynamos in the past that are no longer active, and others carry no record of an intrinsic magnetic field? Why does the system of interacting tectonic plates, with subduction, mid-ocean ridges, and transform faults, play such a major role on Earth, but does not appear on our sister planet Venus or on any of the other terrestrial planets? Is the cycling of water through the Earth's interior critical for plate tectonics, and even for the formation of oceans and life? Understanding the deep interior of our own planet is essential to understanding planetary evolution as a whole.

Educating future scientists

To carry out interdisciplinary research successfully requires preparation in one or more of the disciplines, along with an ability to communicate across disciplinary boundaries. The CSEDI program has provided support for educating students and postdoctoral scholars in different areas of geophysics and geochemistry, while simultaneously providing opportunities for them to participate in interdisciplinary research. Such opportunities prepare students and postdoctoral scholars for scientific success by encouraging them to think about Earth's deep interior as a complex system that requires a multifaceted approach. This is an important role for CSEDI that has an impact beyond that of individual research projects.

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NSF Press Release

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Large Diamonds Made From Gas Are Hardest Yet

High-pressure mineral physics is used to determine how materials behave at the elevated pressures and temperatures within the Earth and planets. The methods developed for studies of the Earth's deep interior contribute significantly to the development of new materials, from new superconductors to large synthetic diamonds having optimal properties. [C.S. Yan et al. (2004) Physica Status Solidi (a) 201, R25] Students who are educated in Earth science are prepared to make contributions to materials science and engineering.

Goals for the future

A Framework for Understanding Circulation in the Deep Earth

New technologies available to the community call for a bold approach to future CSEDI research. It can realistically aim for a broad understanding of Earth's inner dynamics, incorporating core evolution, mantle convection, the driving forces of plate tectonics, and the interaction between the interior, oceans and atmosphere. CSEDI provides a framework for capitalizing on the new observational, experimental and theoretical advances made possible by the current development of major seismological, experimental mineral physics, high resolution geochemical measurements, and computational facilities.

Within the decade, the field is poised to make major advances in understanding:

- Cycling of water and carbon through Earth's deep interior
- Operation and evolution of the geomagnetic dynamo
- Melting and other phase transitions in the deep mantle and core
- Structure and origins of major interfaces in the Earth's interior
- Deep mantle structure, temperature and composition
- Evolution, dynamics and rotation of the inner core
- Chemical and heat exchange between the core and mantle, and between the mantle and the surface.

We organize these emerging research directions into three broad themes for advancing understanding of the Earth as a planet, and connecting Earth-interior processes to the surface. First, quantifying the deep water and carbon cycles would provide a crucial link in understanding how the oceans and atmosphere – and the biosphere they sustain – are linked to the interior, helping to clarify how Earth's surface environment has evolved over geological time. Second, characterizing the deep-Earth engine would provide insight into the forces driving geological processes, including mountain building, earthquakes, volcanoes and plate tectonics. Third, an understanding of Earth's history, the path it took to the present state, offers unique insights into the ways by which planets in general – and our own in particular – originate and develop.

Scientific Themes for CSEDI

Theme 1: The Deep Earth Water and Carbon Cycles

One of the most compelling problems in Earth science is the nature of the carbon and water cycles, which are intimately connected to the climate and biosphere. Although a great deal of progress has been made over the past decade in understanding the carbon and water cycles, the deep-Earth contribution has been difficult to quantify and is therefore largely unrecognized as an important influence. It is well-known that processes originating deep in the mantle, for example volcanic eruptions, can cause sudden changes in climate, but the full cycle of water and carbon through subduction zones and volcanism is poorly characterized.

Influence of the interior on the hydrosphere

Recent work shows that the mantle may house 10 or more oceans' worth of the Earth's water budget. The release of water and carbon by volcanic activity at mid-ocean ridges, alteration of oceanic crust, and recycling of water and carbon into the mantle at subduction zones, completes the overall water and carbon cycle that is also part of the overall flux of mass and energy through Earth's interior. Indeed, the snowball Earth may have been brought to an end by release of volcanic gases, especially CO_2. Methods of deep-Earth research can be applied to characterize this cycle, with the ultimate goal of understanding how the deep interior has contributed to the origins of the hydrosphere and biosphere, and to abrupt and gradual changes in Earth's climate.

Effect of volatiles on the interior

Water also has profound effects on the physical properties of mantle minerals, reducing the viscosity and melt temperatures of rock, and perhaps acting as a lubricant in subduction zones. It has been suggested that the very presence of water on the Earth's surface may be the critical factor that enables the plate tectonic cycle to progress. This idea is supported by the observation that Venus, a planet of similar size and composition, but without surface water, appears to be in a mode of rigid-lid mantle convection, and lacks the global spreading centers, subduction zones and major transform faults that characterize plate tectonics on Earth.

Research needed

Mineral physics experiments and calculations are required to characterize the possible sites for H_2O, CO_2 and other volatile molecules in mantle materials. An understanding of the recycling of water and carbon into the mantle at subduction zones will require the combined efforts of seismology, mineral physics, geochemistry and dynamical modeling. The role of water in controlling the rheology and melting of the mantle must be characterized by experiments and geochemical observations, while the dynamical effects and long-term influence of partial melting and a wet rheology must be better modeled in geodynamics.

Theme 2: The Path to the Present: Evolution of the Earth

To establish viable evolutionary models that lead to an understanding of the Earth today, it is critical to understand the origins and initial state of the Earth, and the factors influencing its early evolution. Such factors ultimately determine how material is distributed within the planet, how the Earth has evolved, and perhaps even why the Earth is a habitable planet.

Initial conditions

The composition of the Earth was likely set primarily as part of a stochastic assemblage of planetesimals that were themselves constructed from the nebular detritus within a feeding zone broadly defined by Earth's present orbit. Key constraints on the chemical composition of the core and mantle are based on assumptions regarding the bulk composition of the Earth. This bulk composition is almost entirely based on comparisons with primitive (chondritic) meteorites, and our models of heat budget, thermal and chemical evolution of the planet depend on our knowledge of this bulk composition.

It is now generally accepted that catastrophic impacts, such as the giant impact that is though to have formed our Moon, played an important role in the generation of the terrestrial planets. This high-energy process would have profound implications for the long-lived chemical and thermal state of the Earth. For example, occasional massive impacts would likely have led to the formation of transient magma oceans. Metal-silicate segregation at the base of a deep magma ocean has been hypothesized as the process that established the abundances of some siderophile (iron-alloying) elements in the silicate mantle. Periodic generation of deep magma oceans would have invariably led to chemical zoning within the mantle, the effects of which may be observable in early Earth rocks and perhaps in the present structure of our planet's interior.

Early tectonic regimes

There is essentially no terrestrial rock record predating 3.9 Ga. Physical evidence of the first 600 Ma of evolution within the inner Solar System is present only on the surfaces of bodies with surviving older crust (e.g. Moon, Mercury, asteroids). Some hints as to the nature of Earth's protocrust can be obtained from the initial isotopic signatures coaxed from early-Earth rocks. The thermal state and implications for cooling of the early Earth can be considered only via models, which must in turn rely on assumptions regarding the internal heat to be dissipated and the distribution of radioactive elements within the Earth.

When plate-tectonic cooling of Earth began remains unknown. There is now considerable evidence that plate tectonics as we know it was established by at least the end of the Archean, 2.4 Ga ago. The thermal regime of the Earth at that time, however, is highly debated. Rapid decline in the production of komatiitic (high MgO, high-temperature) lavas after the Archean is well documented, and may reflect a significant decrease in the temperature of at least the upper mantle. The same general period of time also may mark a period of major growth of the continental crust.

Research needed

Understanding the initial conditions and the early tectonic regimes of the Earth will require a concerted effort of geological observations, geochemical and cosmochemical analysis, dynamic modeling, and paleomagnetic studies.

Theme 3: The Deep Earth Engine

The present-day state and dynamics of the Earth's deep interior provide the key to understanding the forces driving geology. Exploring the internal structure offers a glimpse at dynamics of the interior, but many important aspects remain unclear. The plate-tectonics paradigm of the 1960s established a framework for understanding geological processes at the surface, but it is essentially a kinematic theory, which does not answer how or why the Earth evolves (let alone why other Earth-like planets do not exhibit plate tectonics). Addressing these issues promises to make plate tectonics a truly dynamic, integrative theory that would reveal and clarify connections between the surface environment and the interior. Full characterization of the deep Earth engine is thus a prerequisite for our ultimate goal of understanding Earth-circulation as a whole.

This understanding can emerge from targeted studies of Earth dynamics, including the pattern of large-scale flow in the mantle, the origin of structure in the mantle and the operation of the geodynamo.

The Pattern of Large-Scale Flow in the Mantle

Plate motions are a surface expression of circulation in the mantle. Present-day plate motions establish the pattern of flow at the top of the mantle, but the structure of flow and the driving forces at depth are poorly known. This uncertainty profoundly limits our understanding of the transport of heat, the cycling of water and carbon, and the long-term evolution of our planet. Progress in understanding the present-day circulation has been driven largely by improvements in seismic tomography. Images of lateral heterogeneity in seismic velocity provide a snapshot of structures associated with convection in the mantle. However, the task of converting seismic heterogeneity into quantities of interest for understanding mantle flow remains a difficult challenge. Furthermore, a snapshot of the present-day structure and flow in the mantle does not in itself explain how this state developed. In order to interpret the convective structure of the mantle, we require a comprehensive framework for understanding the origins and interaction of mantle structure. Long-standing questions about the roles of plates, mantle plumes and chemical heterogeneity continue to be vexing problems that limit our ability to predict the evolution of the Earth.

Magnetic field of the Earth

An outstanding challenge that remains is understanding the origins and evolution of the Earth's magnetic field. Identifying the mechanisms driving Earth's dynamo is important to understanding the current rapid rate of change in the magnetic field, the interaction of the Earth with the Sun, and the origins of magnetic field reversals.

The persistence of the Earth's magnetic field for several billion years requires continual regeneration by fluid motions in the liquid iron core because electrical resistance would otherwise eliminate the field in a few tens of thousands of years. Fluid motions stretch and twist the magnetic field lines to produce electric currents that reinforce the field. However, the magnetic field exerts a strong influence on the fluid motion. A remaining problem is to understand how the flow and field are configured to permit regeneration. Numerical models provide a number of working examples, but it is unclear whether any of these examples are relevant for the Earth's field. Identifying the correct mode of operation is important because it is liable to affect the temporal behavior of the field, including reversals. The mode of operation also affects the power needed to run the geodynamo. In turn, the power requirements are closely connected to the evolution of the core and the rate at which mantle convection draws heat from the core. Addressing this problem will require progress from new paleomagnetic observations and synthesis, as well as on the numerical geodynamo front.

Research needed

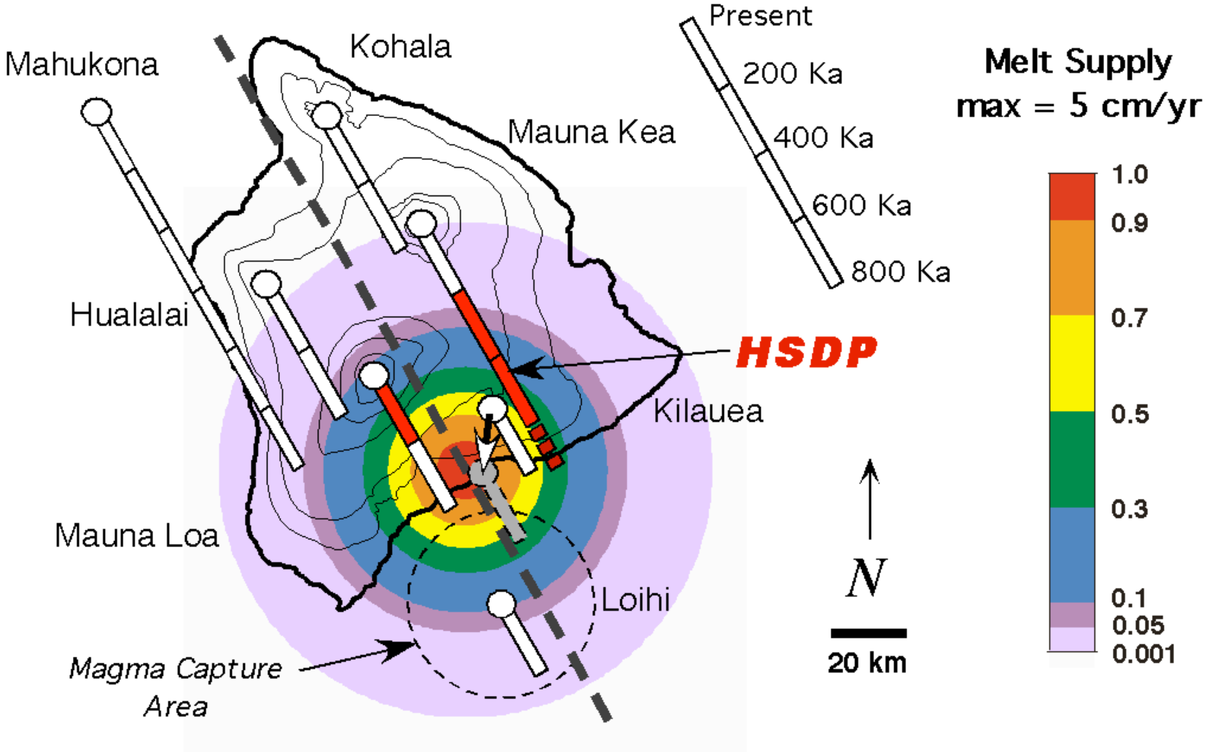
In order to achieve these goals we require advances in mineral physics, seismology, geodynamics, geomagnetism, and paleomagnetism. The two great heat engines in the core and mantle are tightly coupled, so progress in understanding these processes must necessarily rely on an integrated, multi-disciplinary approach. Better and more complete thermoelastic properties for the mantle and core are required to interpret the results of seismic tomography and geodynamo models; better resolution is required of tomographic models; theoretical developments and further observations are also required to deal with more general descriptions of elastic anisotropy and to characterize the scales of heterogeneity in the mantle and core; models and experiments will be required to explore phase transitions in the lowermost mantle; more complete paleomagnetic data are required to understand the evolution of the magnetic field, and better dynamical models are required for both the mantle and core.

Examples of Specific Research Initiatives

With these overarching themes in mind, we have identified specific examples of scientific targets in some of the directions that are ready for significant progress in the next decade. Though they identify initial priorities, these targets are illustrative and not prescriptive. A notable strength of CSEDI research is that many of the key discoveries of the past decade could not have been anticipated at the time that the first CSEDI plan was developed.

Melt in the mantle

Melting has long been recognized as the major process by which the planet differentiates, with Earth's crust (the uppermost 6-80 km layer of rock) having been derived from the mantle through magmatic processes. The importance of melting is not confined to the simple genesis of most of the rocks on which humanity resides: Earth's oceans and atmospheres are likely to have arisen through the magmatic degassing of Earth's interior, and the distribution of radioactive elements — the dominant source of heat in the crust — is completely controlled by geochemical differentiation.



Melt supply of the Hawaiian hotspot [DePaolo et al. (2000) G-cubed] is revealed by the Hawaii Scientific Drilling Projects (HSDP). Combining detailed isotopic measurements with dynamical models of plumes and the resulting melt production (indicated by colors) provide a means to develop the volcanic history of the islands. Understanding the origin and mantle dynamics that produce volcanic hotspots remains a major area of research.

Over the past decade, an appreciation of the critical effects of melting on the uppermost ~3000 km of the planet — the entirety of Earth's rocky shell – has emerged. From the earliest history of planet Earth, when the planet was largely molten due to the heat produced by accretion and initial differentiation of the planet, to the present day, with magmas still being extracted from the mantle and ultimately being either erupted or residing near its top and bottom, melting play a critical role in planetary chemical segregation, in the dynamics of upwellings, and in the degassing of the planet. Magmatic processes are both the cause of major geological hazards (volcanic eruptions and associated phenomena), and the source of important natural resources such as deposits of metallic ores.

Despite their ubiquitous importance in modern Earth sciences, our understanding of magmas and partial melting phenomena throughout the depth range of the mantle is severely limited. Over most of the depth range of Earth's mantle, we have only limited knowledge of the chemical composition of the melts that are formed, and the identities of the residual solids left behind by melt extraction; we do not know how melts are distributed (whether in melt pockets or in intergranular sheets), and thus how they affect the rheology, thermal conductivity, and other physical properties of material at deep-mantle depths; and we have only the vaguest constraints on perhaps the simplest of properties, the density of melts relative to their coexisting solids. The lack of constraints on melt density implies that we do not know whether melts rise or sink from a given depth: a first-order uncertainty on how an initially largely molten (and still partially molten) planet has internally segregated. To resolve such profound issues about melt properties and dynamics requires launching a focused effort in melt studies of the sort that can be accomplished by the CSEDI program.

The Origin of Thermal and Compositional Structure in the Mantle

Increasing evidence for chemical heterogeneity in global tomographic models and detailed regional studies has focused new attention on the origin and role of chemical anomalies in mantle convection. Melting and differentiation at mid-ocean ridges and subduction zones is a key source of chemical heterogeneity in the mantle, but it may not be the only source. Recent suggestions of melting at the base of the mantle and in the transition zone raise intriguing new questions about the possibility of producing chemical heterogeneity much deeper in the mantle. Chemical heterogeneity may also arise from chemical interactions between the mantle and the core. Whether these processes contribute to the anomalous D” region at the base of the mantle or to superplumes below the central Pacific and African remains to be seen. The existence of these structures challenge the conventional view of mantle convection and offer new insights into the dynamics of the deep interior.

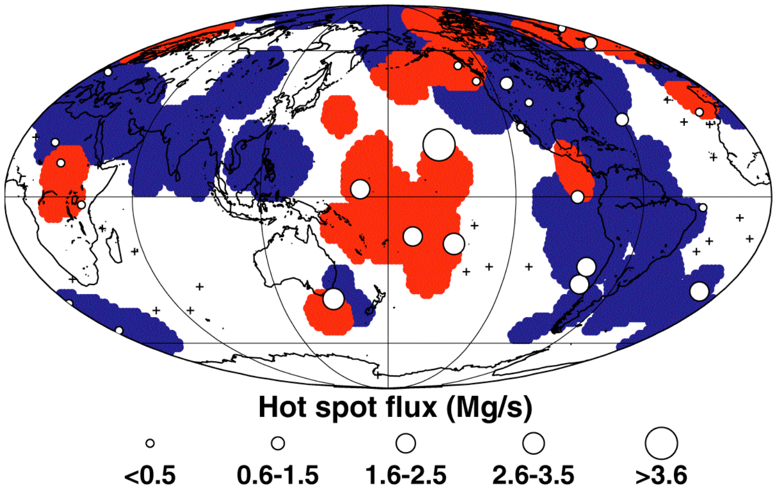
It is customary to assume that seismic heterogeneity arises from thermal anomalies in the mantle. Predictions of the influence of temperature on P- and S-wave velocities are based on available experiments and theory for constituent minerals in the mantle. As the database of relevant mineral properties at realistic pressures and temperatures expands and improves, it has become increasingly clear that seismic heterogeneity cannot be ascribed to the effects of temperature alone. Allowances for the effects of compositional heterogeneity expand the possible interpretation of seismic heterogeneity, and impose new demands for better observations and more comprehensive mineral-physics data, gravity field and surface topography interpretations, and viscous flow models.

One limitation arises from uncertainties in the physical properties of the mantle and another from limitations in the models themselves. Inversion of viscous-flow models to infer mantle viscosity from surface observations provides important insights into the rheology of the mantle. Unfortunately, the results are generally dependent on the limitations of the model. Independent inferences of mantle rheology, either through theory, experiments or other observations, when combined with more realistic physical models of mantle flow, are expected to yield powerful new constraints on the pattern of large-scale flow in the mantle.

Theoretical developments are also required to deal with more general descriptions of elastic anisotropy. This effort is important because images of elastic anisotropy due to crystal alignment can provide a direct measure of the recent history of flow in the mantle. In fact, the incorporation of anisotropy and attenuation into standard tomographic models will greatly enhance the subsequent interpretation of seismic structure.

Understanding interfaces in the Earth’s interior

With new datasets, advances in theory, and greater computational power, deep earth researchers are poised to make major advances in characterizing the interfaces (or strong gradients in material properties) in the Earth’s interior. The existence of major interfaces (including mantle discontinuities, the core-mantle boundary and the boundary between the inner and outer core) is well-established, but many of the features are poorly understood, and several of the interfaces are not yet well characterized. Seismology is making advances in characterizing the depth to, topography on, and regularity of the major known interfaces; knowledge of these features is crucial for our understanding of mantle mineralogy, phase chemistry, and stratification, Earth's evolution, and (mass and heat) fluxes in Earth’s deep interior. For example, there are intriguing suggestions that some mantle plumes pass through the mantle transition zone, while other plumes may originate from shallow depths. Deeper in the Earth, near the core-mantle boundary, partial melting may give rise to patches of ultra-low seismic velocity, while lateral variations in structure or fabric near the top of the inner core may relate to, and provide insight into, compositional convection in the outer core.



The core-mantle boundary is as dramatic an interface within the Earth as the boundary between the crust and the hydrosphere at the Earth’s surface. Seismology has successfully identified extreme variability in seismic velocity at the very base of the mantle. Ultra-low velocity zones (red) may be caused by partial melt, but the features are not observed everywhere (regions in blue lack evidence for an ultra-low velocity zone; after a figure from Garnero et al. 1998). Understanding the relationship between the lowermost mantle and hotspots at the surface (circles) requires research in seismology, geodynamics, mineral physics, and geochemistry.

The study of interfaces is a rich field of cross cutting research between seismology, mineral physics, geochemistry, and geodynamics, linking the study of composition, structure, and heat and mass flow. Over the next decade major advances in our knowledge of interfaces are possible, and collaborative research may yield new probes of deep mantle interfaces. Observational seismology is about to undergo a revolutionary change with the advent of US Array. Although the main objective of this array is to map the mantle directly beneath the US, the US Array constitutes a “seismic telescope” that allows us to peer into the deepest regions of the Earth in ways that have not previously been possible. Interpreting the data will require that seismologists understand better the deterministic and stochastic aspects of scattering, including reflections and seismic mode conversions off interfaces, and the influence of strong seismic velocity gradients. The need to understand scattering and to map small and narrow features (such as plumes), or distant objects (such as the inner core), combined with the need to understand the error and uncertainty in data and models, is prompting theoretical advances in seismology that promise to yield significant improvements in our “seismic sounding” of the deep Earth. To answer questions such as “what is the origin of seismic anisotropy in the deep mantle, transition zone, and upper mantle?” requires collaboration between seismology, mineral physics and geodynamics; advances depend on improved seismological data, modeling, and better posing of the problem, in concert with mineral physics and dynamics research. Understanding the strong lateral gradients associated with large low velocity provinces in the deep mantle will require some advances in 3D seismic modeling and imaging capabilities, together with a reformulation of the problem to include constraints from mineral physics, geodynamics and geochemistry. To characterize global multi-scale heterogeneity will provide a major computational challenge, requiring large-scale computation of 3D models on global and regional scales along with collaboration among seismologists, geodynamicists, mineral physicists, and geochemists.

The Role of Plates on and in Earth Dynamics

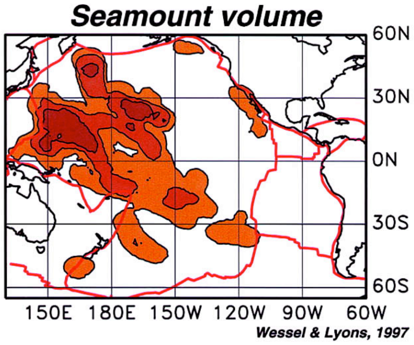
Plate tectonics appears to be a unique feature of convection in the Earth's mantle, yet the influence exerted by plates on the dynamics of convection is largely unknown. It is generally agreed that the motion of quasi-rigid plates at the surface imposes a kinematic constraint on the motion of the underlying mantle, but there is little consensus on anything else. Some view plates as a simple thermal boundary layer, with a direct analogy to textbook models of convection. Others see plates as a key factor in organizing the structure of flow.

In order to make progress on this issue, we need to understand the processes that control the evolution of plate boundaries and the initiation of new subduction zones. Geodynamic studies will require better rheological models for the deformation of Earth materials, including the weakening influences of water. We also need to integrate geological records into the modeling studies, both in terms of past plate motions and the associated deformation at plate boundaries.

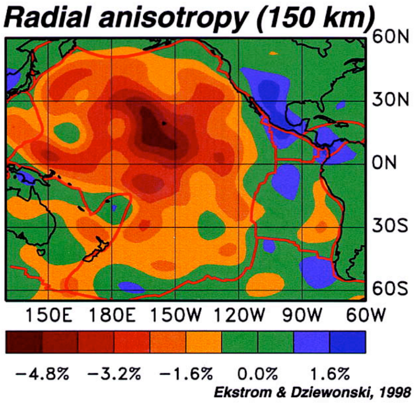
In reality, complexity in rheology, variability of thermal conductivity, and phenomena such as phase transformations may well lead to "mantle avalanche" type behavior and episodic cooling events of the lower mantle. How this translates into variations in the growth rate of the inner core and the consequences for the geomagnetic field remain open questions. Thus, it is essential to improve models of the silicate earth, because our exchange and mixing models critically depend on the data determining the concentration differences and isotopic contrasts between the core and mantle. Our understanding of the inner core, a region that appears remote from the surface, is in fact intimately linked to our understanding of the mantle and the crust.

Origin of Hotspots

Hotspots are thought to be the surface expression of mantle plumes. The depth and source material for plumes continues to be a contentious issue, but these questions are crucial for interpreting geochemical signatures in lavas that erupt from hotspots. Seismology has started to make important advances in imaging conduits below a number of hotspots. In many locations the conduits extend into the lower mantle, although there appears to be no simple model that explains all of the observations. Numerical and laboratory studies of plumes in a convecting fluid have made important progress in quantifying the dynamics of plumes under a wide range of conditions. Current efforts to combine seismological studies with geodynamic modeling and detailed geochemical analysis hold great promise for further advances.


Seamount volume

Wessel & Lyons, 1997


Radial anisotropy (150 km)

Ekstrom & Dziewonski, 1998

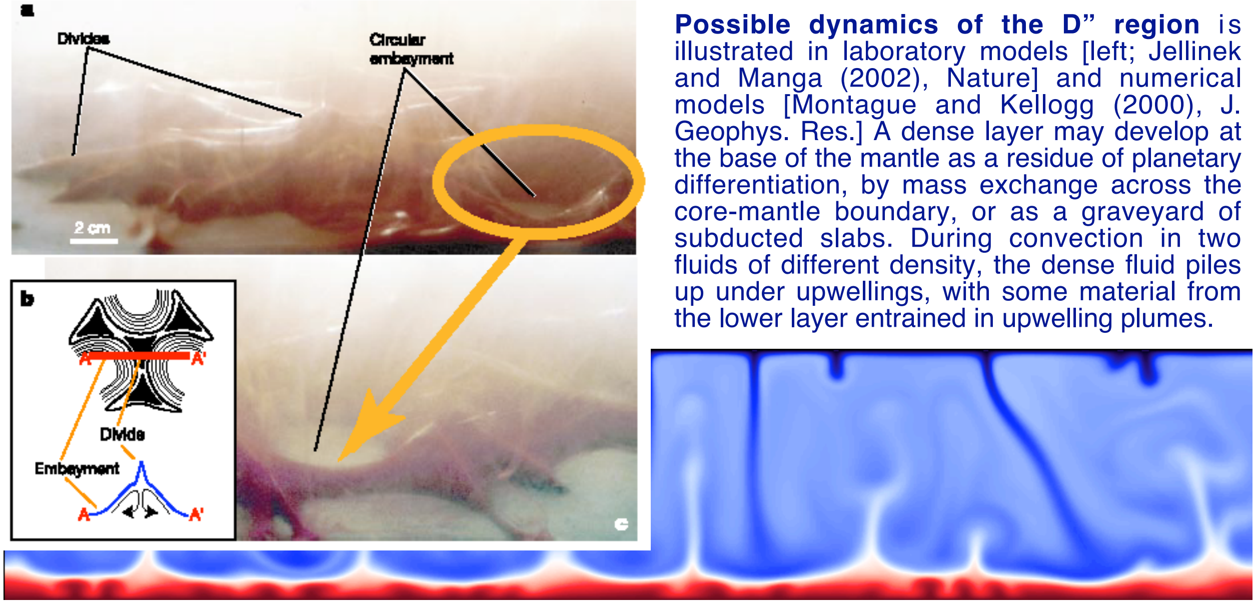
Central Pacific anisotropy reaches a maximum of 130 km depth [lower right; Ekstrom and Dziewonski, (1998) Nature]. It is not known whether the anisotropy is associated with the thermal event that built the seamounts [seamount volume in upper right; Wessel and Lyons, (1997) J. Geophys. Res.].

Mass and Heat Fluxes

Geological activity is characterized by the movement of materials and heat on scales ranging from global (~10^3 km) to regional (~10 km). Indeed, convection of the mantle and core, the action of plumes, movement of tectonic plates at the surface, and infiltration of magma and other fluids at depth offer dramatic examples of Earth’s ongoing planetary evolution.

The geological record provides an integrated history of our planet’s mass and heat fluxes. Through seismological, geodetic, heat-flow and magnetic observations, geophysics yields information about the current dynamics of the interior; and the geochemical signatures of magma source regions and of direct (xenolith) samples from the interior provide a means of tracking the time scales of these internal processes. Information about the properties of Earth materials, derived from petrology and mineral physics, and the full range of geological, geophysical and geochemical observations is combined and interpreted through geodynamical models.

Tracking of mass and energy (heat) fluxes lies at the heart of understanding how our planet has evolved over geological time. What is the differential motion of fluids at depth, leading to volcanism and metamorphism due to upward migration of fluids and heat toward the surface? What is the potential for downward sequestration of hydrous (and other volatile-bearing) fluids, or even of dense oxide or metallic melts in the deep interior? How effectively is heat transmitted upward across the core and then the thickness of the mantle, providing the energy sustaining the geomagnetic field as well as the plate-tectonic processes observed at the Earth’s surface?



Possible dynamics of the D” region is illustrated in laboratory models [left; Jellinek and Manga (2002), Nature] and numerical models [Montague and Kellogg (2000), J. Geophys. Res.] A dense layer may develop at the base of the mantle as a residue of planetary differentiation, by mass exchange across the core-mantle boundary, or as a graveyard of subducted slabs. During convection in two fluids of different density, the dense fluid piles up under upwellings, with some material from the lower layer entrained in upwelling plumes.

It is also this heat flow from the interior that provides the energy for colonies of micro-organisms exhibiting ancient genomic characteristics. It is thus possible that life originally established itself in regions where it could feed off the Earth’s internal heat.

The key to understanding these phenomena is to recognize that each process of mass and energy flux leads to a wide range of geological consequences. That is, although one may have to work at the state of the art of a given specialty in order to make significant observations, the interpretations need to be broadly linked across the disciplines.

As an example, imaging of plumes remains a major challenge for seismology, especially at great depth in the mantle. How can spatial variations in wave velocity and attenuation be resolved with adequate sensitivity to track the sources of such major surface features as Hawaii and Iceland? The difficulty of imaging the mantle at the required scales has led to vigorous discussion of the origins and dynamics of hotspots. Meanwhile, observations of geophysical anomalies must be interpreted in the light of geochemical and geological information about the temporal evolution of these regions, and all of the data must be woven together into reliable geodynamic models of mantle tectonics and magma "plumbing."

Such models offer a means of quantitatively peeling back Earth history, revealing the processes by which our planet has evolved over geological time and perhaps a glimpse into its origin and earliest history. But in order to validate the models, it is essential to formulate them in terms of testable hypotheses. Continuing with the example: Given a seismologically-determined plume structure, including the uncertainties and resolution limits imposed by the observations, what are the associated geodetic and geochemical anomalies that would be expected? What new observations are required either to refine the model, or to falsify its underlying hypotheses? How can laboratory experiments be brought to bear most effectively on the interpretations – Is it more important to determine elastic-wave velocities or trace-element partitioning among mineral phases at conditions relevant to plume sources, for example?

Structure and Evolution of the Inner Core

The inner core is an important target for investigation; its structure and history have implications for the origin and evolution of the magnetic field, and for the thermal and chemical evolution of the Earth as a whole. Calculations using new experimental or theoretically determined properties of iron alloys at extreme temperatures and pressures indicate that the inner core could grow to its present size in less than 1 billion years, but these calculations raise questions about the thermal evolution and earliest geological history of the planet as a whole.

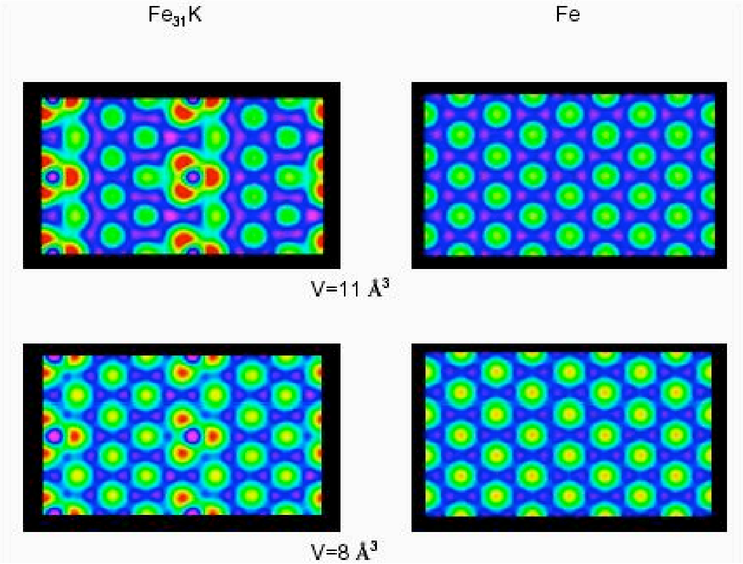
We know the Earth has had a magnetic field for most of its history so, either the inner core is not essential to dynamo action or the assumptions that enter into the calculations of inner-core age are flawed. For example, light material rising from the inner core surface may form a sub-adiabatic stable region at the top of the outer core that would reduce the amount of heat being lost by the core, or there may be significant radioactive heat generation within the core itself. The latter would have significant implications for the distribution of heat-producing elements throughout the whole Earth.

Specifically, to understand the inner core requires researchers to:

- Compute or measure thermodynamic and elastic properties of iron alloys at temperature and pressure conditions appropriate to the inner core.
- Determine flow structure in the core, with particular emphasis on determining whether there is a stably stratified region at the top of the core.
- Determine whether the character of the magnetic field and its reversal rate have changed over the age of the Earth.
- Determine the partitioning behavior of elements between silicate and potential core forming liquids at high pressures and temperatures in order to better constrain the planetary heat budget and place constraints on the age of core formation.

- Determine the W and Ag isotopic composition of plume-derived basalts to test further models of core-mantle exchange at the CMB and constrain the age and growth history of inner core.
- Develop more realistic geodynamo models to put better constraints on the power requirements for the dynamo.

Of course, the evolution of the inner core is ultimately controlled by the thermal history of the mantle, making the study of the inner core an interdisciplinary problem of global significance. To date, thermal history calculations of the mantle have typically used parameterized results from numerical experiments at relatively low Rayleigh number and using simple rheologies, resulting in models that predict a monotonic history of cooling.



Quantum mechanically calculated electronic charge densities for iron (*right*) and a $K_{0.03}Fe_{0.97}$ alloy (*left*) at volumes corresponding to pressures of about 0 (*top*) and 100 GPa (*bottom*) have been used in conjunction with high-pressure experiments to show that potassium could be alloyed into the Earth's core in sufficient quantities to be a significant source of heat due to the decay of naturally occurring ^{40}K [K. Lee *et al.* (2004, *Geophys. Res. Lett.*].

What is needed

Support for integrated research towards solving targeted problems

One of the major accomplishments of the CSEDI program has been an increase in interdisciplinary research and communication between disciplines. A continued goal of the CSEDI program should be to foster and support interdisciplinary research, training, and integrative activities.

In recent years the NSF CSEDI program has funded a range of proposals on the kind of interdisciplinary research that contributes to CSEDI goals. Most of the sponsorship has been of pairs or small groups of investigators for durations of 1-3 years. For the first four years of the program, the budget was limited to $1M/year, and has grown since that time to an expected level of $2M in FY05. While accomplishments under the existing program have been significant, the modest size of CSEDI's current budget has limited the style and scope of research funded, with typical grants for 2-5 PIs ranging from

$150 K to $850 K (at peak program budget levels). Although larger-scale projects with budgets several times higher have been favorably reviewed within the program, limited resources have made it impossible to support them. Significantly more resources would be required to foster a number of different styles of collaborative research, in order to enhance the community's ability to make rapid and substantial progress towards targets of interest.

Group Collaborations

The success of the CSEDI program is built on small-scale collaborations of multiple PIs, each bringing specific expertise to a project. Essentially, CSEDI has functioned as a small-grants program with the additional requirement that the work be interdisciplinary or multidisciplinary. The resources of the existing program have often been stretched in funding such projects, because interdisciplinary work usually requires funding multiple PIs at several institutions. A further limitation has been the short duration of projects. Interdisciplinary collaborations often require more time to develop than research projects by individual investigators.

The CSEDI program should continue to fund group collaborations, but resources need to be allocated to allow for the possibility of longer duration, and larger grant sizes, with more collaborators, than can currently be funded. A reasonable project length may be closer to 5 years than the current typical 2-3 year grant.

Grand Challenges

One mechanism for facilitating significant progress is for the community to formulate one or more grand challenges, with the goal of dedicating adequate resources to solving a problem that is perceived as particularly important to the framework for understanding circulation in the deep Earth. One or more of the specific targets described above might form the basis for such a grand challenge; we emphasize that such challenges must emerge from the deep-Earth research community in response to emerging needs and opportunities and be vetted through the peer-review process.

Integrative activities

In addition to direct support of research, our understanding of the deep Earth would benefit from a variety of integrative activities designed to support the overall goals of CSEDI. Such integrative activities could include educational programs for graduate students and postdoctoral researchers, interdisciplinary workshops, the establishment of integrative centers where CSEDI–like research can be conducted, support for community computer resources, and development of databases designed for interdisciplinary data mining.

Preparing future scientific leaders

Such integrative activities are essential to gain the greatest benefit from CSEDI research. We view CSEDI as a model for developing a strong cohort of cross-disciplinary scientists who can become leaders of U.S. science, in industry, government, and academia. Among other benefits, CSEDI is ideally suited to offering the cross-disciplinary educational and research background that future scientific leadership will require. A student or postdoctoral scholar supported by CSEDI benefits from interacting with several PIs addressing cutting-edge research problems, and using complementary approaches from distinct fields. That trainee can therefore benefit from working on a specific scientific problem while also acquiring a multi-disciplinary education. The CSEDI program has successfully contributed to the career development of young scientists. Grantees have gone on successful careers in academia and have won awards for early-career scientists. CSEDI offers the requisite scientific environment, but those willing to take on the challenge of pursuing multi-disciplinary science must be adequately supported. A broader background than ever is required in order to make significant cross-disciplinary advances in geoscience research. At the same time, a deep knowledge of physics, math, and chemistry is required to carry out fundamental research on the Earth. This puts considerable pressure on those being trained, graduate students and postdoctoral fellows, who must now become technically capable in a wide variety of sub-disciplines: from continuum mechanics and fluid dynamics to petrology and isotope geochemistry. Such training offers enormous advantages, however, in ensuring a full preparation for leading – let alone engaging in – scientific research and education of the 21st Century. It is therefore important that NSF programs, such as CSEDI, exist that supports the education of scientists for these research efforts of such groups.

Internet presence

Both science and education in deep-Earth studies would benefit from the development of a community internet website. This internet presence would serve as a virtual meeting point for CSEDI members, with links to various CSEDI-related web sites, a resource for electronic discussion and dialog of the community's views on the present structure and direction of CSEDI, and a posting of announcements relating to CSEDI activities. The CSEDI community should collectively develop ways in which to relate our science to those in related sciences, as well as others beyond our community. There is a desire in the community to bring our science and its insights to as wide an audience as possible, especially the general public and in particular to the next generation of scientists, policy makers, and leaders who are presently developing in K-12 classrooms around the nation.

Coordination and management

A modest management structure may be required to serve the community in a number of CSEDI-related functions (i.e., as a point of contact, to disseminate information by developing and maintaining an Internet presence, to promote and facilitate links within and between CSEDI and other interested communities, to carry out administrative tasks, etc.). For example, a Coordination Committee was formed to develop this document to reflect the expressed goals of the CSEDI community. An ongoing Coordination Committee may be needed to continue to facilitate and promote CSEDI activities. The CSEDI community would benefit from having a more coherent voice for the community and from developing a means to relate the accomplishments and goals CSEDI to others in the earth and planetary science communities and to the broader public. An active Coordination Committee would look for means to further the goals of CSEDI and build bridges to other groups and initiatives. The community needs to not only bring together its, but to also find ways in which to implement them or facilitate their implementation. The CSEDI Coordination Committee would convene regularly to consider and evaluate the current and future developments in CSEDI. It would further the goals of CSEDI through community interaction, meetings and sessions/symposia at international venues. This committee would be expected to deliver to funding agencies the views of the CSEDI community. Developing, maintaining and upgrading such integrative activities and an Internet presence for CSEDI requires not only commitment of individuals but also the commitment of resources, such as support for salary, administration, travel, and support for an Internet site. These costs would have a limited impact on CSEDI's annual research budget while at the same time supporting much-needed activities of CSEDI.

Community Meetings

The community believes that much of CSEDI's agenda can be accommodated within the framework of existing schedules for meetings and conferences, thus there is no need to promote a dedicated CSEDI meeting cycle. For example, the highly successful SEDI meetings provide an international forum for the presentation of new deep earth research. However, from time to time the need may emerge for topical CSEDI meetings or workshops that should be supported by the CSEDI program. A CSEDI Coordination Committee could assist with organizing and promoting such meetings.

Synthesis Center

The NSF has, in partnership with other agencies, funded significant new infrastructure for observing, simulating and modeling the Earth's interior, from seismic arrays and synchrotron beamlines to modern clusters of computers. So much data is becoming available that the research community is hard-pressed keeping up with it, even though it is exactly these new observations that have led to many of the key discoveries of the past few years.

The community is convinced that there remains a deeper level of analysis to be pursued, involving cross-disciplinary study and extension of the results that have been streaming in. Given the increasing technical demands in each sub-discipline, however, there is little opportunity to pursue such multi-disciplinary efforts; individual research areas have developed different terminologies and concepts, and it is ever more difficult to make connections among these disciplines.

Therefore, the community has recognized the need for a synthesis center, in which active researchers and leading members of different sub-disciplines could begin working together – in cross-disciplinary fashion – in analyzing the major new data sets now becoming available: in short, to obtain full return on the investment that has been made in new and existing research infrastructure. This was the conclusion of an NSF-sponsored international workshop held at Marconi Center, California in May, 2003.

The proposed CIDER initiative provides an example of such a center, combining educational components with multidisciplinary research and even the planning of future research. On the one hand, it is necessary for the disciplines to better understand each other's approaches and accomplishments, from seismology and isotope geochemistry to geodesy and geomagnetism. Thus, education of the new generation of students and young researchers is essential to the development of the field, and this can be accomplished through workshops, short courses, and web-based tools. On the other hand, in order to truly exploit existing data, let alone the stream of new data anticipated over the coming years, it is crucially important to organize cross-disciplinary teams that can study particular problems or data sets from multiple approaches.

A synthesis center can provide an effective venue for researchers from different sub-fields to pursue focused research targets over limited periods of time, from a few days to a few months. Such targeted projects would result in uniquely cross-disciplinary publications, and these could help define new research directions to be funded at high priority by the CSEDI Program. A synthesis center may be able to take on some of the integrative activities described above, such as coordination, management and outreach for the CSEDI community; efforts should be made to avoid duplication of effort to ensure the maximum impact of such integrative activities.

We emphasize that cross-disciplinary studies can only succeed in a community with strong expertise in each of the underlying disciplines. For this reason, the traditional grants to individual investigators are all-important for sustaining the intellectual vitality of the CSEDI community. However, given a research community that is strong in the disciplines and yet has great potential (and desire) for multidisciplinary work, there is an opportunity for considerable value added in providing a forum for defining and beginning to pursue cross-disciplinary studies. CSEDI is such a community, and the value of a synthesis center would be to greatly enhance the effectiveness of the research that such a diverse group of researchers can pursue. A center of this kind would also help establish the next generation of young scientists to become knowledgeable leaders in broadly-based research and its application for societal benefit.

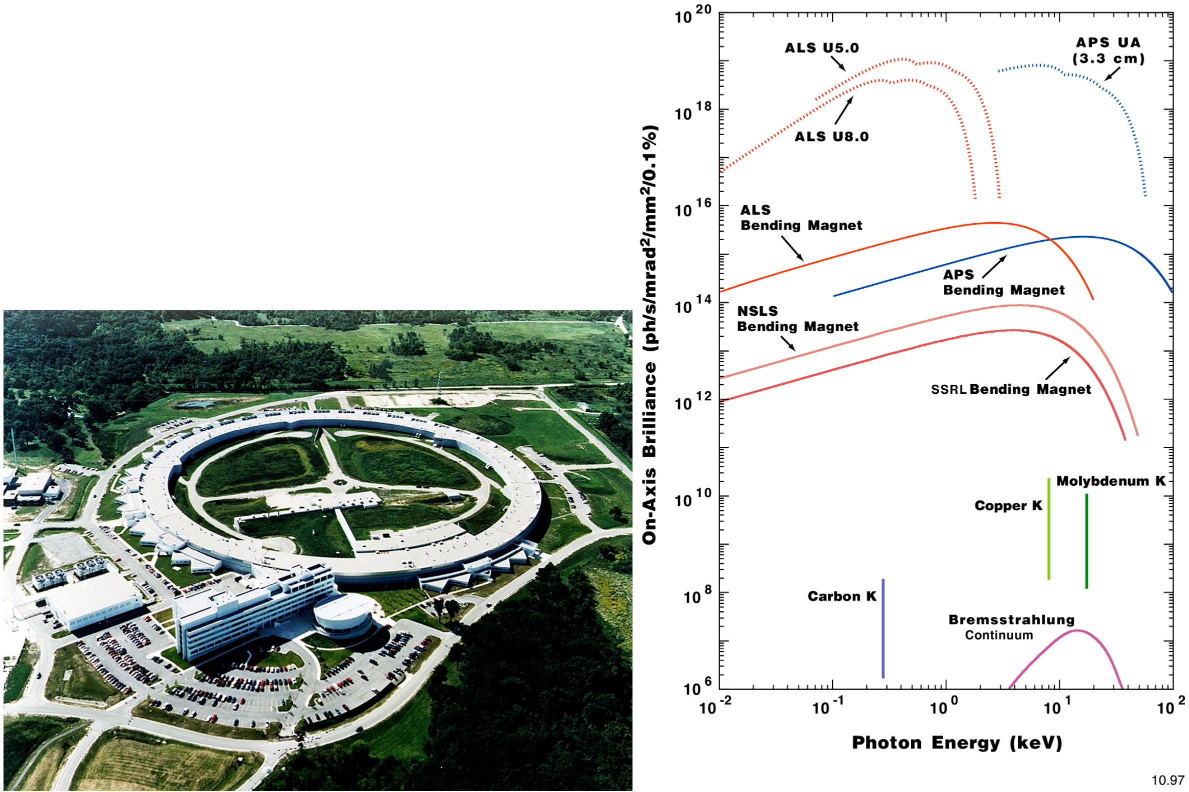
Summary of Needs

To extend the success of research into Earth's deep interior, the CSEDI program needs to provide more support for both collaborative research and integrative activities. In addition to the inherent benefits of interdisciplinary research, both research and integrative activities would complement and extend the value of disciplinary and cross-cutting research conducted under other programs. A reasonable level of support for CSEDI would be to fund approximately 10 new projects per year supporting 2-5 PIs, ranging in size from $200k to $2M/project. Such an investment would require an annual funding level of $5M. This would allow the program to entertain projects with a wide range of styles, ranging from small teams of investigators working on focused problems to projects headed by larger teams with broader scientific scope. In addition resources should be allocated for larger projects and integrative activities as demonstrated by successful peer reviewed proposals. We envision a program with a full portfolio growing up to $10 M over the next decade.

Appendix: Resources and infrastructure to be exploited

Both the quality and quantity of observations have improved dramatically over recent years because of significant developments in the field as well as the laboratory. High-resolution seismological imaging, the application of sophisticated geochemical analyses, and the ability to experimentally simulate deep-Earth conditions have seen major breakthroughs in technology and research collaborations. An important benefit of the CSEDI program is to increase the scientific value of these resources and infrastructure.

For example, the availability of major facilities, from large seismic arrays to synchrotron beamlines, has been paralleled by the emergence of the large interdisciplinary research teams that are required to make full use of the new facilities. Spanning a broad range of specialties, these groups have revolutionized the collection of geophysical and geochemical observations. Although the CSEDI program cannot (and should not) fund large infrastructure directly, we anticipate that the CSEDI community will continue to be synergistically involved in the development of facilities and methods.



Synchrotron radiation, such as from Argonne National Laboratory's Advanced Photon Source (APS: shown in aerial view), has revolutionized X-ray diffraction by providing beamlines with at least 6-8 orders of magnitude more brilliance than conventional laboratory sources (e. g., copper and molybdenum K lines shown in the spectrum). Infrared spectroscopy has similarly been enhanced by improvements of 5 orders of magnitude over the intensity of conventional laboratory sources.

Example 1: Total Beamlines

Major user facilities such as synchrotron and neutron beamlines offer unique opportunities for performing cutting-edge experimental research on materials and at conditions directly relevant to deep-Earth studies. In particular, it is possible to simulate the high pressures and temperatures existing deep inside Earth and other planets, and to conduct sophisticated measurements of material properties *in situ*, at these conditions. The new NSF Consortium for Materials Properties Research in Earth Sciences (COMPRES) provides support for the operation of beamlines at these national facilities to ensure access for Earth science students and staff, as well as for infrastructure development projects designed to enhance the usefulness of synchotron and neutron facilities.

One of the significant developments accompanying the establishment of 3rd-generation radiation sources has been the recognition that the beamlines are now so thoroughly developed that their operation can recede into the background. That is, they are sufficiently reliable that the focus can now turn away from beamline operation to adding highly sophisticated experiments. In order to truly characterize the melting of rock or metal characteristic of planetary interiors, for example, it will be necessary to combine demanding experiments giving the molecular-scale structure (diffraction and spectroscopy based on the beamline) with laser spectroscopies and other sophisticated methods for determining elastic properties (e.g., phonon spectroscopy) and transport properties (viscosity, thermal diffusivity) across a sample held at high pressures and temperatures. Other properties of great importance for deep-Earth study include equilibrium partitioning of elements between phases, chemical diffusivities, electrical conductivity and (an)elastic-wave attenuation within samples, all of which can and should be measured while the state of the sample is being characterized at the beamline.

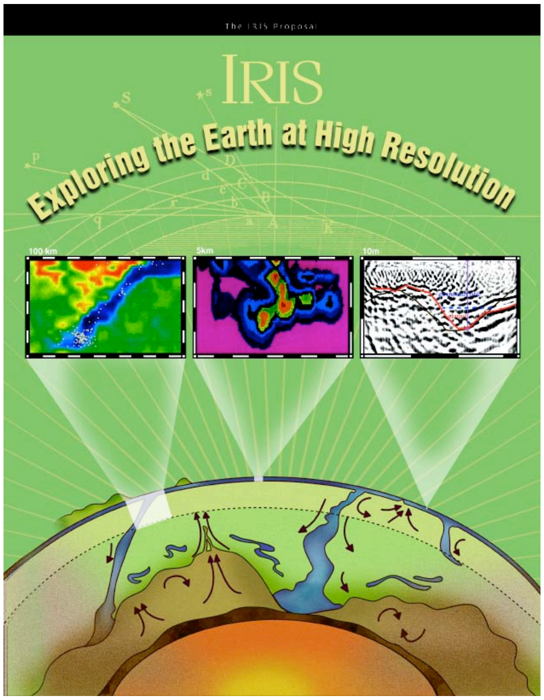
Each of these measurements is currently possible on its own, but is just within the realm of technical capability. An opportunity for a quantum leap in information is possible, however, if one can combine these methods, for example to provide multiple independent means of characterizing when a sample is melting at elevated pressures and temperatures (and, at the same time, provide important new physical and chemical measurements on the melt and on the solid just before melting). Such measurements are further leveraged by tying them closely to modern computational developments in quantum and statisitical mechanics (including molecular dynamics): theory can make quantitative predictions and helps greatly in the interpretation of the experimental measurements, but is also advanced by determining how well it agrees with the data.

Because of this potential for significant technical advancement in deep-Earth experimental research, there is considerable emphasis within the community supporting facilities and infrastructure in developing “total beamlines;” that is, by instrumenting x-ray and other beamlines for multiple, highly sophisticated experiments allowing complete and simultaneous characterization of materials at deep-planetary conditions. The simultaneity is important, because independent measurements on the same sample at the same conditions is the only means of reliably determining properties at the extreme pressures and temperatures of planetary interest.

The science involved is intrinsically multi-disciplinary, and CSEDI offers a uniquely suitable means of supporting such research and development. At the most immediate level, the collaboration of many groups ensures that calibrations become well established, so that quantitative results can be obtained (i.e., with minimal and well-determined uncertainties). More significantly, geochemical, geophysical and other measurements can be performed in order to characterize links between the properties relevant to each of these disciplines. For these reasons, CSEDI should leverage the technical advances being made at major user facilities by supporting the cross-disciplinary research required to develop this new generation of experiments, and apply the results to understanding the Earth’s deep interior.

Example 2: Seismic networks

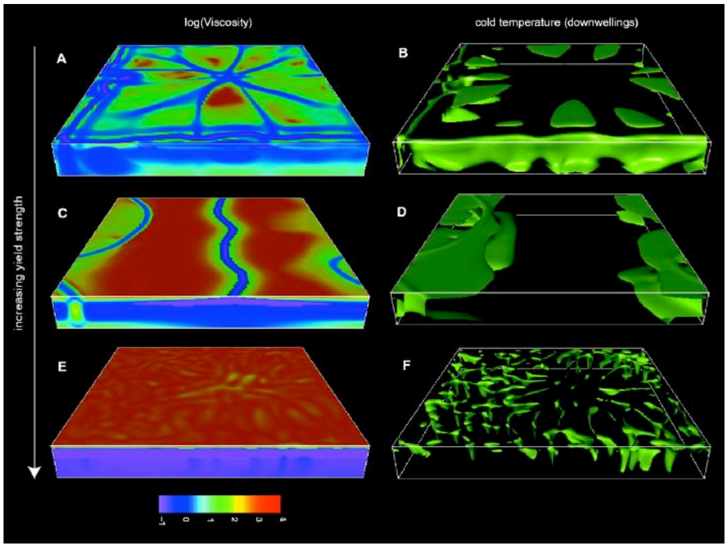
Progress in seismic tomography has largely been tied to the expansion both in type and size of the datasets used in tomographic model construction. Dramatic increases in the number and density of stations through Earthscope will permit seismologist to develop and implement new imaging methods, such as those based on scattering theory, to obtain unprecedented resolution of deep-earth structure. At present, sampling of some parts of the mantle (particularly some regions in the southern hemisphere's lowermost mantle) remains poor, and is only incrementally improving with time. The fundamental reason for this is the geographic distribution of sources and receivers at the surface of the Earth. Almost all possible land sites have now been developed, including many of the islands in the Earth's oceans, and further progress will require ocean bottom observatories. Deployment of ocean-bottom seismometers are crucial for filling the gaps in current coverage. Of course, seismology is only one of many sciences that would benefit from ocean-bottom observatories, and there are now several initiatives afoot to make such observatories a reality. The CSEDI community is extremely interested in seeing these initiatives succeed.



Seismic networks make it possible to investigate Earth's structure at a variety of scales, as illustrated by the cover of the 2000 IRIS proposal to the National Science Foundation. The facilities of the IRIS Consortium, supported by the NSF, support a broad range of studies of Earth's interior.

Example 3: Computational Infrastructure

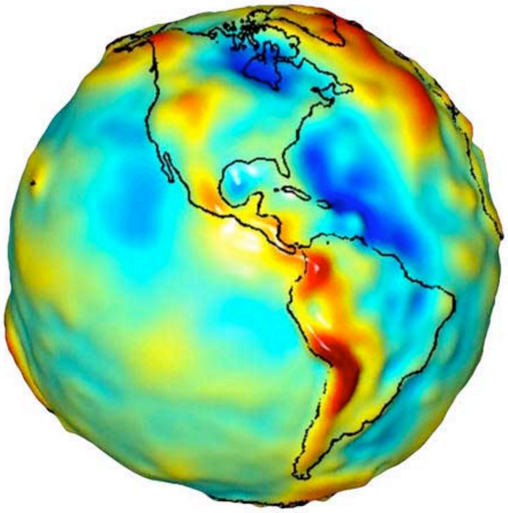
Computation continues to be a powerful tool for understanding deep Earth structure and dynamics, with models of the geodynamo and mantle convection pushing the limits of modern computing facilities. To realistically represent, for instance, plate boundary processes in a model of mantle convection may require grids that span scales ranging from meters to thousands of kilometers in a single model. Such problems require state of the art computational methods and the accompanying computational and memory power. Likewise, new approaches to mineral physics, using *ab initio* calculations, place extraordinary demands on existing computer resources. Seismology is also a science that needs huge computational power. It is now possible to compute complete theoretical seismograms on a 3-D Earth with anisotropic and anelastic structure up to periods of a several seconds. This requires the computational power of the biggest computers on Earth, such as the Japanese Earth Simulator. Access to such power will allow us to take much better advantage of the information content of seismic waveforms than is currently the case. Deep-Earth researchers have been users of major computer resources including the National Supercomputing Facilities, as well as developing localized mid-sized computing systems with individual clusters of processors dedicated to solving specific scientific problems. We anticipate that this need will continue to grow, keeping pace with the development of available computer resources. It is critically important for NSF to provide these resources in a rational way for deep-Earth research.



Computer simulations of mantle convection and plate-tectonic phenomena require the most advanced hardware and software currently available. Numerical experiments such as those shown can reveal the role of material properties such as yield strength in determining lithosphere and mantle-flow processes, ultimately helping to explain why Earth alone (and not our twin neighbor Venus, for example) exhibits plate tectonics [P. Tackley (2000), Science].

Example 4: Space-based observations

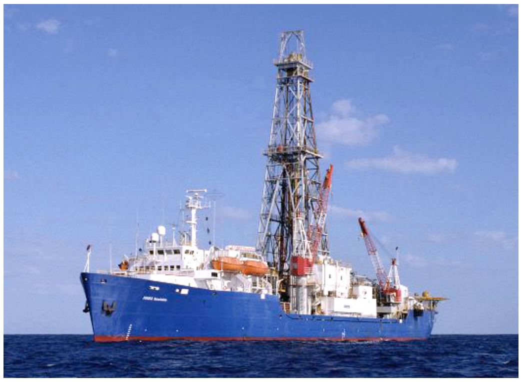
A number of ongoing and planned space-based observations will impact the study of the Earth's deep interior. The current International Decade of Geopotential Research has stimulated programs that have led to the planning and launch of a number of satellites to measure the magnetic and gravitational fields (Ørsted, CHAMP and SAC-C, CHAMP, GRACE, GOCE and Swarm). For example, current and planned magnetic satellites provide detailed information about the structure of time variations in Earth's magnetic field, and also record the electromagnetic response of the Earth to variations in the magnetosphere. These observations sample the electrical conductivity deep into the mantle, providing information about bulk composition, temperature and volatile content. Similarly improved, time-varying measurements of the Earth's gravity field, will facilitate better interpretations of the interior structure of the mantle and core as well as hydrological and tectonic phenomena. The continued collection of, and ready access to, these data is important to CSEDI researchers.



Gravity model from the Gravity Recovery and Climate Experiment (GRACE) satellite shows the influence of deep earth structure on Earth's gravitational field.

Example 5: ODP and IODP

Marine sediment cores collected under auspices of the Ocean Drilling Program have proved enormously useful in studies of the structure of the paleomagnetic field, making it possible to address questions about the deep earth such as whether mantle plumes are fixed, the nature and evolution of the Earth's magnetic field, the processes that occur during magnetic field reversals, the location of the Earth's magnetic axis, and the history of tectonic plates. The advent of the new Integrated Ocean Drilling Program (IODP) extends the international collaboration on ocean drilling by applying new technologies to basic research problems requiring oceanic drilling.



The JOIDES Resolution is a scientific research vessel operated by the ODP and currently by the IODP. The Resolution has been providing scientific data since 1978.

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GRACE Gravity Model 01 Americas http://www.csr.utexas.edu/grace/gallery/gravity/ggm01_americas.html
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Earth's magnetic field is generated in the liquid **outer core**, where fluid flow is influenced by Earth rotation and the **inner core** geometry (which defines the **tangent cylinder**. Core fluid flow produces a **secular variation** in the magnetic field,which propagates upward through the relatively electrically insulating **mantle** and **crust**. The crust makes a small static contribution to the overall field. Above the insulating **atmosphere** is the electrically conductive **ionosphere**, which supports **Sq currents** as a result of dayside solar heating. Outside the solid Earth the **magnetosphere**, the manifestation of the core dynamo, is deformed and modulated by the solar wind, compressed on the sunside and elongated on the nightside. At a distance of about 3 Earth radii, the **magnetopsheric ring current** acts to oppose the main field and is also modulated by solar activity. Magnetic fields generated in the magnetosphere and ionosphere propagate by **induction** into the conductive Earth, providing information on electrical conductivity variations in the crust and mantle. **Magnetic satellites** fly above the ionosphere, but below the magnetospheric induction sources. [Constable, C.G., & S.C. Constable, (in press, 2004).]

The Geomagnetic Earth