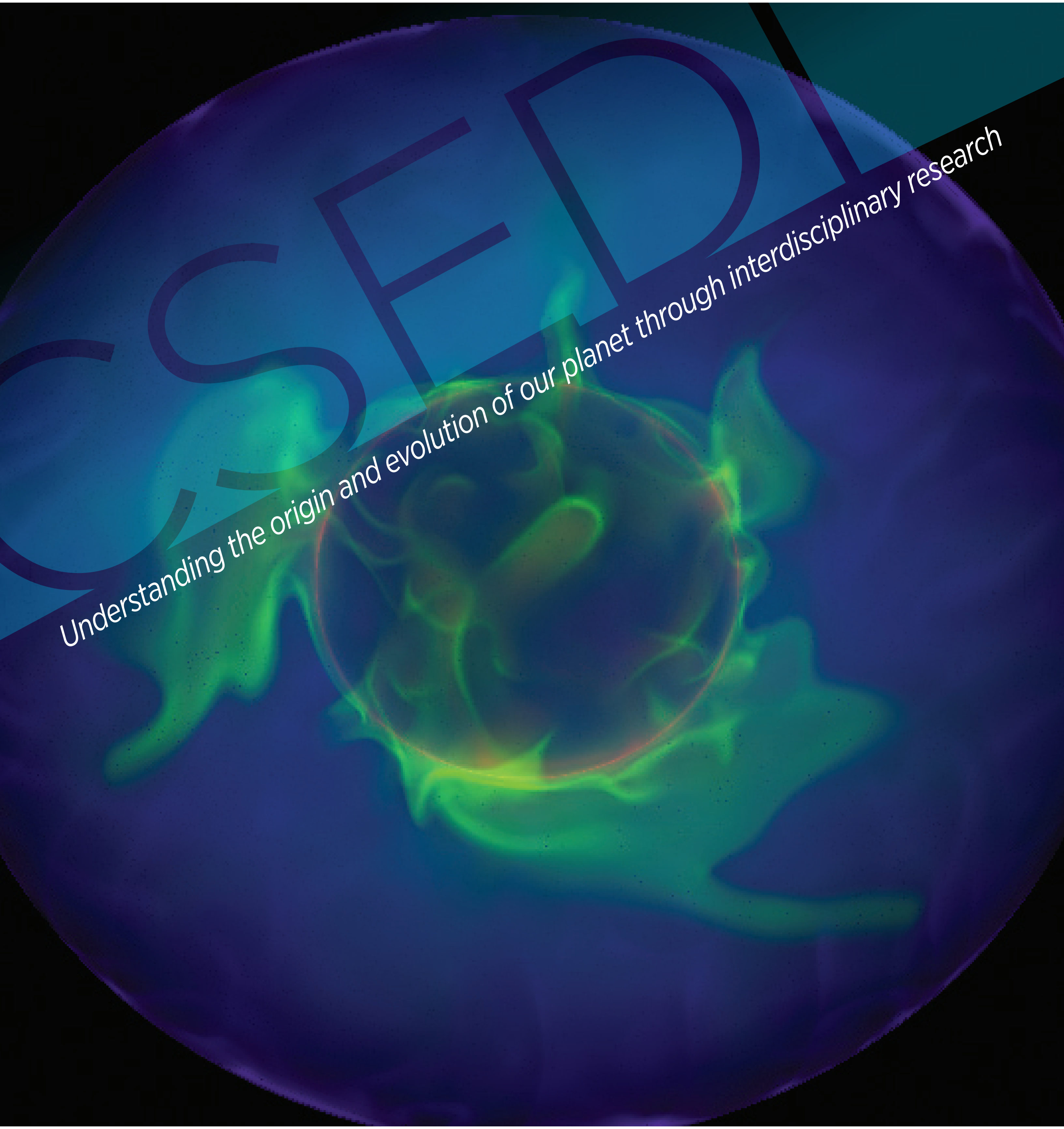
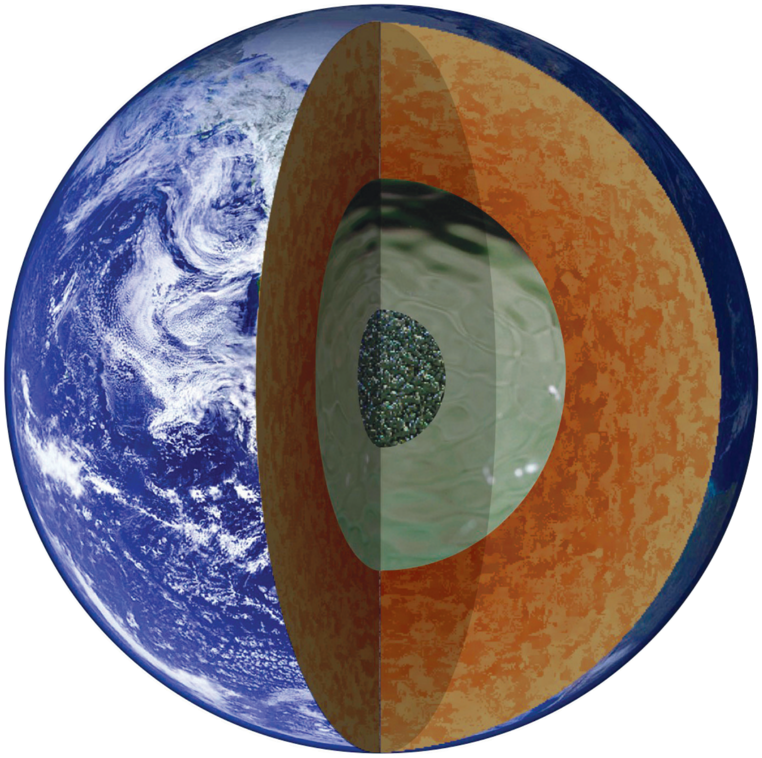
COOPERATIVE STUDIES OF THE EARTH'S DEEP INTERIOR





This report presents a synthesis of community discussions from a workshop on Cooperative Studies of Earth's Deep Interior (CSEDI) attended by over 75 researchers and held at Scripps Institution of Oceanography, UC San Diego from January 21-22, 2015. The workshop was used to discuss the accomplishments and benefits of NSF's cooperative CSEDI program targeting Earth's deep interior, and to evaluate new questions requiring our attention. The committee members listed below were responsible for production of this report. They thank the numerous researchers who contributed material, while acknowledging their own responsibility for its content and accuracy.

Report Writing Committee

Bruce Buffett, *University of California, Berkeley*
Cathy Constable, *University of California, San Diego*
James Day, *University of California, San Diego*
Marc Hirschmann, *University of Minnesota, Minneapolis*
Shun-Ichiro Karato, *Yale University*
Louise Kellogg, *University of California, Davis*
Maureen Long, *Yale University*
Wendy Mao, *Stanford University*
Guy Masters, *University of California, San Diego*

Please cite this report as follows:

Constable, C.G, T.G. Masters, B. Buffett, J.M.D. Day, M. Hirschmann, S-I. Karato, L. Kellogg, M. Long, W. Mao, (2016) COOPERATIVE STUDIES OF THE EARTH'S DEEP INTERIOR: Understanding the origin and evolution of our planet through interdisciplinary research, available from csedi.org/2016_Report

Cover: Volume rendering of temperature field from a geodynamo simulation using Calypso, a set of codes for MHD dynamo simulation in a rotating spherical shell using spherical harmonics expansion methods (courtesy Hiroaki Matsui).

Above:Internal Structure of the Earth (courtesy Eric King)

COPYRIGHT CSEDI.ORG, FEBRUARY 2016

EXECUTIVE SUMMARY

The National Science Foundation's (NSF) program on Cooperative Studies of Earth's Deep Interior (CSEDI) established 20 years ago enables unique forms of cooperation across the Earth Sciences and beyond. Work within and across multiple disciplines is integrated to provide fundamental understanding of the origins of our planet, its current state, and important connections between the deep interior and surface conditions. This report presents a synthesis of CSEDI community discussions from an NSF sponsored workshop held at Scripps Institution of Oceanography, UC San Diego, in January, 2015. Three broad themes were endorsed for future work: (1) **Early Earth**; (2) **Deep Earth Engine**; (3) **Deep Earth to Surface Interactions**.

Research on the early Earth deals with the formative events that set the initial trajectory of our planet's evolution. Recent accomplishments have challenged long-held assumptions and altered our perspective of the Earth in a broader planetary context. Observations of diverse planetary systems around other stars is one example. Advances in analytical capability for measurement of short-lived isotopic systems offer new and surprising insights into materials forming the basic building blocks. Outstanding questions about giant impacts and the subsequent cooling of magma oceans are coming into sharper focus with advances in computational modeling, better measurement of early geochemical signatures, and refined estimates of the phase diagrams and equations of state spanning solid, liquid, and vapor phases relevant to a much hotter planet. A key goal of this work is to understand in general terms the transitions that lead to the present-day state, including the onset of plate tectonics and the development of clement conditions at the surface.

The current state of the planet reflects distinct heat engines connected by a complex boundary region separating Earth's core from the mantle. Emerging patterns of mantle flow and increasingly refined knowledge of deep-seated seismic structures challenge mineral physicists, geochemists, and geodynamical modelers to provide a coherent view of the composition and dynamical state of the deep mantle. In the outer core questions remain about composition, conductivity, and whether the geomagnetic field is sustained by convection throughout the whole core or parts of the flow are stratified. Their resolution requires improved knowledge of thermal history, core structure, composition and phase diagrams, together with better links between geodynamo simulations and paleomagnetic results.

Advances in study of volatile storage and fluxes in Earth's interior have led to a new understanding of the important role of the mantle in maintaining equable conditions on Earth's surface and modulating the dynamics of its interior. Fluxes of H_2O, C, and N into and out of the mantle via magmatism and subduction maintain continental freeboard, Earth's climate and atmosphere, whilst their storage in the mantle has significant effects on mantle rheology and hence the vigor of convection, the locus of melting, and interior geochemical differentiation. These deep Earth volatile cycles operate over time scales ranging from the age of the Earth to short-term events such as the influence of large igneous provinces on ecologic crises or possibly the termination of glacial maxima. Understanding the participation of the core in deep Earth volatile cycles, both during original differentiation of the Earth and subsequently, remains an important challenge

Much has been accomplished, but remaining challenges require new focus and resources. CSEDI has drawn on and contributed to multiple programs across NSF and elsewhere, enabling a strong impact from a rather small program. The time is ripe to increase the scale of the program enabling additional larger projects that can capitalize on efforts to date.

TABLE OF CONTENTS

I. INTRODUCTION

The geological activity and surface habitability of our planet is determined by its internal dynamics. Mantle convection and plate tectonics sculpt the surface of the present-day Earth, while convection in the liquid iron core sustains the geomagnetic field which in turn protects us from deleterious impacts of the solar wind. It is now certain that Earth had a cataclysmic beginning. The initial condition is set by giant impacts during accretion leading to extremely high temperatures and extensive melting and vaporization. The details of this traumatic beginning are important and can significantly affect how our planet evolved. An interplay between geological observations (geochemical, petrologic, paleomagnetic, etc.) and geodynamic modeling is needed to understand what happened at the dawn of time and how we evolved to our present state.

Collaborative scientific work has driven increased understanding of Earth's formation and evolution and of the processes that control its current structure, composition and internal dynamics. Through these efforts it is possible to understand our world, the connections between Earth's deep interior, its surface structures, and surrounding environment. Such understanding is increasingly important in the Anthropocene, a period where changes in our dynamic world must be understood in relation to past events, with an appreciation of the interconnectedness of processes throughout the Earth System.

More than two decades 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 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 (CSEDI, 1993). The CSEDI plan envisioned a framework within which to foster cross-disciplinary research that would transcend traditional intellectual and institutional divisions, and this was made possible by support from the NSF CSEDI program established in 1996.

CSEDI is a special program that sits within the Deep Earth Processes part of EAR, a division of NSF's GEO directorate. It is distinguished from the core science programs (Geophysics, Petrology & Geochemistry, Tectonics, Earthscope) by broadening the scope of research beyond the immediate specializations of individual participants. The nature of interdisciplinary research in the program is very broad, and CSEDI projects have involved multiple kinds of cooperation and collaboration across a broad range of scales. These include:

- projects like reference models, where the majority of the effort may largely draw on one discipline (e.g., seismology, geochemistry) but has an impact on (and is a service to) other disciplines
- small interdisciplinary collaborations, either within a single institution or at several institutions
- infrastructure for training and high-level education
- synthesis projects that integrate work from multiple disciplines
- people bringing distinct techniques to solve a problem, e.g. linking laboratory and field observations
- drawing in researchers from outside EAR (e.g., OCE, ATM, Polar) and outside GEO (mathematicians, computer scientists, material scientists, etc.).

These collaborations have provided a bonding force across disciplines revising attitudes to approaching research problems, opening new opportunities and allowing an integrated understanding of deep earth processes. It is imperative that this view of how to conduct deep Earth research continues, engaging an expanded collection of expertise in future research. Such cooperation across disciplines, while requiring initial impetus, has gained significant traction, with a cross-disciplinary community that has developed an unprecedented level of expertise for studying deep earth dynamics; we can expect substantial scientific rewards over the next decade.

In 2004, the CSEDI plan emphasized building a framework for understanding circulation in the deep Earth, and significant progress has been made in a number of areas in the past decade. At a workshop in January 2015, community researchers assessed where we stand and by consensus proposed to focus on three main themes to address important unresolved questions in Earth Science.

The first theme on the *Early Earth* deals with processes and conditions that set the initial state of our planet. Research in this area is increasingly integrated into the broader study of planetary formation, which has undergone dramatic progress with the detection and characterization of planets around other stars. Effective use of short-lived isotope systems is another factor that has transformed our understanding of processes and timescales in the earliest stages of the solar system. The second theme on the *Deep Earth Engine* delves into the processes that have brought the Earth to its present state and govern its evolution into the future. Convection in the Earth's rocky mantle and liquid iron core are separate, but coupled processes that lie at the very heart of our planet's geological activity. Substantial improvements in the quality and quantity of geophysical measurements have combined with remarkable advances in experimental methods and a steady growth of computational capability to transform the field. We live in a golden age, where a detailed and predictive understanding of the Earth's internal dynamics seems within reach. The third and final theme on *Deep Earth to Surface Interactions* reflects a growing understanding that climate and surface processes on long-time scales are strongly influenced by processes in the Deep Earth.

All three of these research themes were identified in a recent NRC report on New Research Opportunities in the Earth Sciences (NROES). The NROES report identified seven areas in which investment was expected to bring important returns. Three of these areas are directly connected to CSEDI topics, including the (i) Early Earth, (ii) Thermo-Chemical Internal Dynamics, and (iii) Interactions Among Climate, Surface Processes, Tectonics and Deep Earth processes. A fourth area on the Co-evolution of Life, Environment and Climate is related to CSEDI topics because the environment and climate in our planet's thin outer veneer are controlled on long timescales by processes in the interior.

In this report we elaborate on each of the three research themes summarizing recent accomplishments and identifying future goals that can be realized through a multidisciplinary approach. We first consider the broader impacts and benefits of engaging in such research. In addition to contributions to GEO Priorities and Frontiers, these include basic research ranging from particle physics to planetary science, technological impacts in computer and data science, and public engagement on topics ranging from basic literacy about the origins and workings of our planet, to why the geomagnetic field reverses polarity, and what makes the planet habitable today. We outline the educational resources needed for training both disciplinary and interdisciplinary scientists of the future (e.g., CIDER), and the infrastructure needed to facilitate further progress on CSEDI themes, touching on connections to work funded by other agencies both nationally and internationally.

II. BROADER IMPACTS

The value of the cooperative and interdisciplinary links like those forged over two decades within the CSEDI program is now widely acknowledged as an essential strategy for future NSF research. The 2009 GeoVision report from the GEO advisory committee outlined a series of challenges related to understanding and forecasting the behavior and complexities of the Earth System calling for a public role in the geosciences and highlighting the need to appreciate societal impacts arising from Earth processes. A follow-on report in 2012 focused on strategic frameworks for data and informatics, facilities, international relationship and activities, and education and diversity.

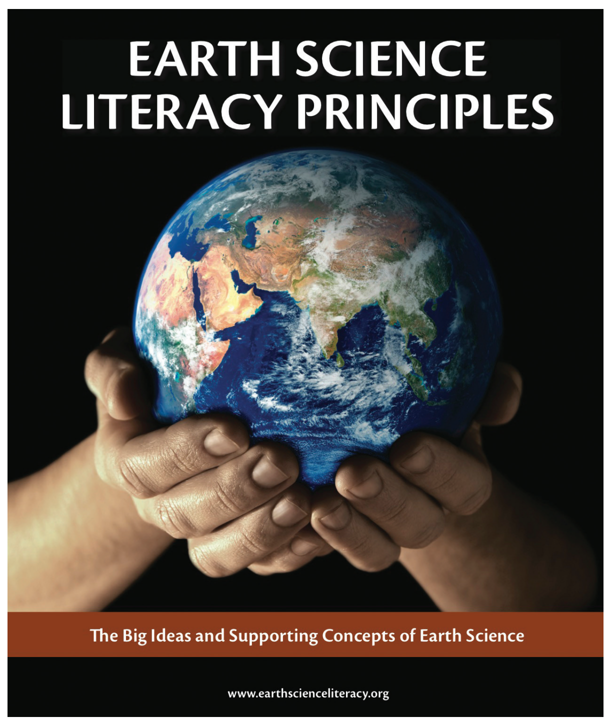
Societal implications for deep earth research

The importance of deep earth research for society at large is made plain by the need for both research and public education on natural and anthropogenic hazards. Earthquakes have long been appreciated as a threat to the built environment. More recently society has acquired an increased respect for the need to understand space weather and the interactions between the solar wind and the geomagnetic field. On the longer term we know that changes in the volume of ice sheets lead to tectonic signals associated with postglacial rebound dependent on the viscosity of the mantle. Understanding these signals is necessary to provide corrections for improved hydrological models. And we know that volatile cycling through Earth's deep interior plays an important but not yet fully defined role in the water and carbon cycles, and relatedly to Earth's climate. Teasing out the multiple disparate contributions to these various signals remains important to our understanding of the Earth System.

In addition, technological impacts following from computational and technological developments associated with CSEDI research are discussed below.

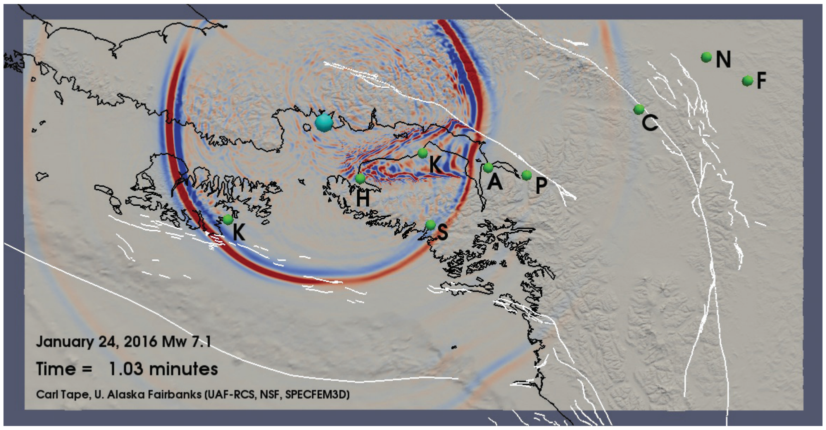
Fostering international cooperation

CSEDI's roots are firmly established in a global approach to science. The international organization known as SEDI (Studies of Earth's Deep Interior established in 1987 is a Union Committee of the International Union of Geodesy and Geophysics (IUGG). SEDI's ultimate goal is an enhanced understanding of the past evolution and current thermal, dynamical and chemical state of the Earth's deep interior and of the effect that the interior has on the structures and processes observed at the surface of the Earth. SEDI leads a biennial symposium with substantial US participation, and CSEDI fosters and participates in training programs that involve international students. Many CSEDI projects also make use of international infrastructure in seismology, mineral physics, and other fields.



Educating future scientists

Research in Earth's deep interior is inherently interdisciplinary, requiring scientists trained in one or more core discipline as well as an ability to communicate across disciplinary boundaries. Over the past decade, programs such as CIDER (Cooperative *Institute for Dynamic Earth Research,* www.deep-earth.org see page 9) have fostered interdisciplinary engagement by a diverse group of early career scientists through tutorials, summer programs, and by seeding small team research projects. In addition, IRIS, COMPRES, CIG, and other NSF funded infrastructure offer specialized tutorials in the tools and techniques required for research in seismology, mineral physics, and geodynamics. This meets a need in that many graduate programs find it impossible to offer such broad training to their students.



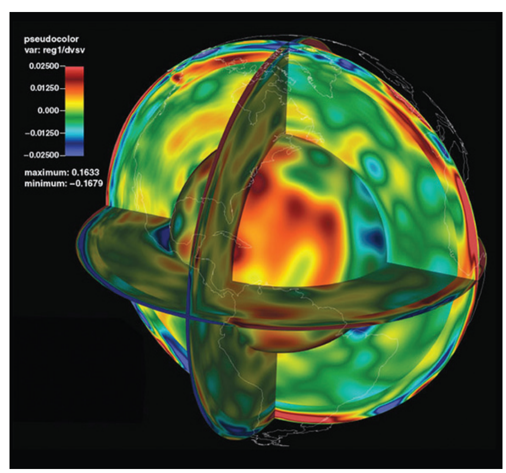
Computer simulation of a magnitude 7.1 earthquake on January 24, 2016 in the Cook Inlet region of Alaska. The simulation region is 1200 km x 600 km; A = Anchorage, and F = Fairbanks. The 3D simulation demonstrates the complexity of the seismic wavefield that arises from realistic models of Earth structure. We see a striking effect due to the slow wave speeds within Cook Inlet sedimentary basin, between points H and K. The simulation was performed on the high-performance computing cluster at the University of Alaska Fairbanks, Research Computing Systems. The 3D wave propagation code is called SPECFEM3D. Image courtesy of Carl Tape, U. Alaska. www.giseis.alaska.edu/input/carl/research/earthquakes/iniskin.html

Training the next generation of scientists requires reaching K-16 students in addition to graduate students. The Earth Science Literacy Initiative (http://www.earthscienceliteracy.org/), in defining principles for understanding our planet, has recognized that students should understand how scientists study the deep Earth and its role in Earth systems. CIDER involves high school physics teachers in its summer programs with a deep-earth focus; deep-earth research is also featured in education modules at the Science Education Research Center at Carleton College.

Public engagement

The dynamics of Earth's deep interior, the origin of Earth and its evolution through time is fascinating to the general public. Hundreds of news stories are generated in the mainstream media, and scientists whose research was funded by the CSEDI program engage in public outreach on a broad range of topics. Examples include:

- **Television documentaries:** The Peabody Award-winning COSMOS: A Spacetime Odyssey, broadcast in 2014, features deep earth research in at least two of its thirteen episodes. Astrophysicist Neil deGrasse Tyson dedicates an episode to plate tectonics, including the underlying deep earth driving processes, while an episode on magnetism delves into planetary dynamos.
- **Earthquakes and volcanic eruptions:** Geological events, especially natural disasters, create a demand for rapid and accurate information. Experts in Earth's deep interior are frequently called upon to explain the mechanisms and impacts of large subduction-zone events to the general public. The communities operating infrastructure to support research typically also support this rapid outreach, providing data, images, and animations that scientists can put into use immediately in their teaching.
- **Mineral physics:** Topics as varied as the origins of diamonds, the nature of the Earth's core, and the potential danger posed by the state rock of California (serpentinite), have all captured the public imagination; deep earth researchers engage in this discussion through broadcast and print media interviews, social media outreach, and contributions to museum exhibits.



Full waveform tomography of Earth's mantle computed through a partnership between Princeton University deep-earth researchers and the DOE INCITE program. The model was computed on Titan, at the Oak Ridge Leadership Computing Facility. Image courtesy of Ebru Bozdağ, University of Nice Sophia Antipolis, David Pugmire, Oak Ridge National Laboratory, and Jeroen Tromp, Princeton University.

Technological impacts: Computational Science, Data Science, and Mathematics:

Computational modeling and data inversion have become essential techniques for deep-earth research. Molecular-scale modeling was critical for characterizing post-perovskite; advances in computational seismology and the ready availability of seismic data enabled imaging the mantle and crust at high resolution, facilitating discovery of structures and fabrics; and development of new scientific software enabled novel investigations of the thermal evolution of the mantle, the structure of subduction zones, and the origins of the Earth's magnetic field. These accomplishments require engaging computational scientists, applied mathematicians, atmospheric and solar physicists, and computational materials science and influenced the scientific developments across these fields. Deep earth research has established a culture of making data and scientific software openly available and is a model for other scientific disciplines.

Modeling the circulation in Earth's outer core that powers the geodynamo or computing full-waveform tomographic models of the Earth's deep interior requires large scale computations; this need has led deep-earth researchers to establish partnerships with DOE's INCITE program at Argonne and Oak Ridge National Labs. These programs provide access to leadership class computing through allocations of computing resources and expertise on effective use of some of the world's largest computers for scientific applications.

Facilities and techniques

Deep earth researchers use a variety of advanced, interdisciplinary facilities including beam lines, the National Ignition Facility, seismic arrays, geodetic networks, and computing facilities. The broader impact of deep earth research includes the partnerships with physicists, materials scientists, engineers, mathematicians, computer scientists, and astronomers who develop and use these resources. Today, we have access to the entire pressure-temperature range of planet formation. This significant experimental capability is new and will yield valuable new insights into the process of Earth's formation. A description of some of the key infrastructure and facilities is included in Section VI.

CIDER

As research on the Earth's deep interior becomes increasingly multidisciplinary, there is a growing need to change the way we train the next generation of researchers. Many of the exciting future developments are likely to occur at the boundaries of traditional disciplines, so it is important to develop a workforce that is prepared to cross disciplinary boundaries in the course of their own research. The Cooperative Institute for Dynamic Earth Research (CIDER) was created with support from the National Science Foundation to address the needs of CSEDI research. Senior graduate students and postdocs are brought together each summer under an organizing theme to identify the key research questions, based on the perspectives of the major disciplines in Earth Sciences. Once students become familiar with the terminology and tools of the various disciplines, they are better positioned to pursue new lines of research that acknowledge the weaknesses and exploit the strengths of the various disciplinary approaches. The CIDER program has been effective in promoting research that ultimately leads to strong CSEDI proposals and more rapid research progress.

Poster session and research group at KITP 2012

III. EARLY EARTH: FORMATION AND EVOLUTION

Earth has reached its present-day state through over four and a half billion years of dynamic activity - plate tectonics, volcanism, asteroid and planetesimal impacts, mountain building, weathering, climatic variations and the rise of life have all contributed to the planet's evolution. Recent discoveries suggest that fundamental characteristics of the present-day Earth have their origin in processes that occurred within tens to a hundred million years of its formation. Here the challenges are to understand this early, energetic history, and the consequences of this formative period on the Earth.

Planetary Formation and Composition

Accomplishments

Major advances have been made in the last decade in understanding the accretion and formation of planets. Some of this progress has been motivated by the discoveries of exoplanets, which reveal significant diversity in planetary architectures. Numerical simulations of planetary accretion demonstrate that even the largest planets can migrate substantially from the position of their initial formation. Migration of planets the size of Jupiter and Saturn can disrupt the accretion of smaller planets and alter the provenance of material that contributes to the innermost terrestrial planets. Increasingly, these simulations are used to inform our understanding of the Earth's initial state. Predicted changes in volatile content and redox state of the accreted material are now routinely used to guide models of core formation and interpret isotopic anomalies.

Numerical models of planetary accretion also reveal a prominent role for giant impacts in the growth of terrestrial planets. Impacts large enough to produce the Moon (Fig. 1) were probably common in the earliest Solar System. It is also evident that impacts do not always yield a simple merger of two bodies. High-velocity impacts may strip off the crust and mantle of the impacted body leading to significant geochemical fractionations on differentiated bodies, such as Earth. Evidence for rapidly cooled iron meteorites suggest that this process has also occurred on smaller bodies. Collisional erosion has also been suggested to account for the large core of Mercury.

Recent progress in our understanding of giant impacts and the aftermath have produced numerous surprises in the past few years. Prior to 2012, it was thought that angular momentum constraints of the Earth-Moon system imposed severe restrictions on the size, velocity and orientation of the impacting body. In smooth particle hydrodynamic models, the best agreement was achieved with the impact of a Mars-sized body (often called Theia) into the proto-Earth. However, these models have led to a geochemical conundrum, since such models also indicate that much of the lunar mass is made up from Theia materials, yet the isotopic compositions of both Moon and Earth are essentially identical.

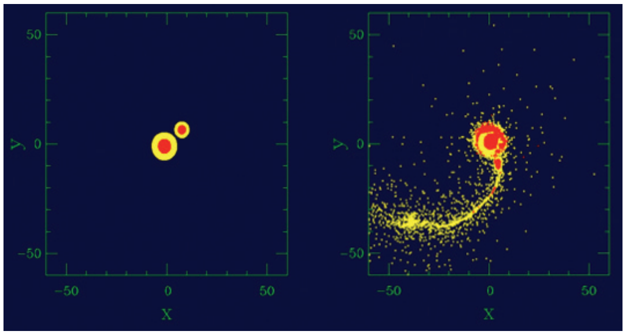


Figure 1. Two time-slices in the animation of a glancing impact into the proto-Earth (from (Canup, 2004)). The silicate mantles of the planetesimals are shown in yellow while their cores are red. The first image is slightly before the impact whereas the second is taken after about two orbital rotations of the central object. In this image, the silicate mantle of the impactor has been dispersed into orbit while the impactor core has mostly been accumulated onto the central object. This type of separation suggests that in an impact of this sort, the material placed into Earth orbit that would re-accumulate to form the Moon, mostly derives from the impactor, not the Earth.

A number of models have been proposed to account for the identical isotopic composition of Earth and the Moon. One is that both bodies had very similar initial compositions due to their formation in the inner Solar System. This form of model can be investigated by further high-precision analysis of lunar and terrestrial samples and, ultimately, sampling other planetary bodies, particularly Venus. A recent alternative proposal is that high-temperature chemical equilibration between the Earth and Moon occurred, leading to isotopic equilibration in a vapor/melt disk shortly after the impact (Fig. 2). The idea of an isotopically similar zone in the inner solar system also needs astrophysical investigations to understand mixing of the earliest solids (dust and planetesimals).

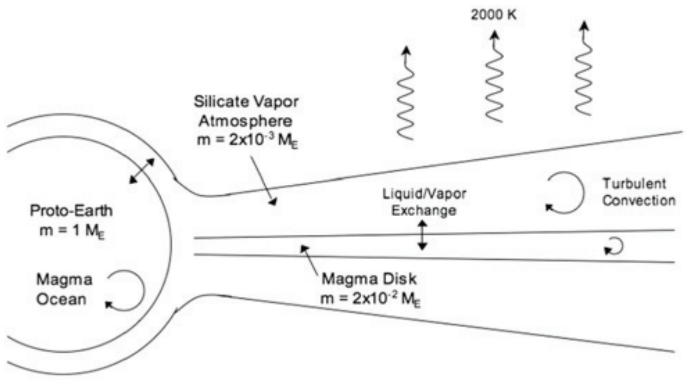


Figure 2. Schematic representation of the liquid/vapor disk surrounding the Earth shortly after giant impact. Substantial chemical exchange between the Earth and the surrounding disk can occur, potentially explaining the similarity in composition between Earth and Moon, in the absence of alternative collision models (from Pahlevan and Stevenson, 2007).

Since 2012, several studies have invoked impact scenarios that are different from the "canonical" Mars-sized impactor. One study proposed an impact between two similar sized bodies; another involved a small impactor on a fast-spinning proto-Earth. These models have very different implications for the state of the planet after the impact. However, we still need an explanation for the unique isotopic similarity between the Earth and Moon.

Improvements in geochemical measurement capabilities have accompanied these advances in our understanding of accretion processes. Two recent accomplishments stand out as being particularly significant, and both have involved improvements in chemical separation and measurement procedures. The first is the suggestion of a non-chondritic Earth composition from the ^{146}Sm – ^{142}Nd isotope system. This discovery came from the observation that the amount of the isotope ^{142}Nd in the Earth differs from chondrite meteorites, the assumed building blocks of planets, by about 10-20 parts per million. The measurable difference translates to a large (~5%) difference in the amount of the parent isotope, ^{146}Sm in the Earth compared with chondrites and indicates that the bulk mantle of the Earth is non-chondritic with respect to Sm/Nd. Loss of a primitive crustal layer through collisional erosion is one possible interpretation to explain this difference, due to the significant fractionation of Nd from Sm that occurs during partial melting. However, there is currently no physical model to explain erosion of the Earth's early crust in the manner invoked by geochemists. We need physical models that quantitatively link the process of collisional accretion to changes in chemical composition.

The second discovery involves isotopic anomalies of tungsten isotopes in terrestrial mantle-derived lavas, in research that was supported by the NSF CSEDI program. Both Nd and W isotope anomalies, while different in detail, could only have been imparted in the first 10-200 My of Earth history. Persistent Xenon isotopic anomalies imparted within the first 100 My have also been discovered between the deep and shallow mantle. The fact that these heterogeneities have been preserved within the deep Earth means that we have a measurable legacy of chemical conditions within earliest Earth. Further understanding of these mantle heterogeneities, combined with the exciting potential of geoneutrino detection to measure the heat-producing element (K, Th, U) distribution within the Earth (see page 18) have implications for both the mode of terrestrial accretion, efficacy of mantle stirring and for the evolution of Earth's atmosphere.

Future Directions

The Sm/Nd composition of accessible materials on Earth are distinct from chondrites, and measurements of other key ratios, such as He/Ne, are contributing to a vigorous debate about the chondritic Earth model. These differences could be explained by fractionation of elements either due to incorporation of materials with non-chondritic character, or due to fractionation in high velocity collisions or during hit-and-run collisions (Fig. 3). A mix of dynamical models, experiments to deduce equations of state of key materials, to enable us to link the physical processes to the chemical outcomes, and geochemical observations are required to resolve these issues.

Unlike the Nd and W anomalies, the Xe anomalies between the shallow and deep mantle still appear to persist in the modern day mantle. It is becoming clear that the anomalies in the various short-lived isotope systems are being erased on different timescales. Addressing why this is so may relate to issues as broad as stagnant

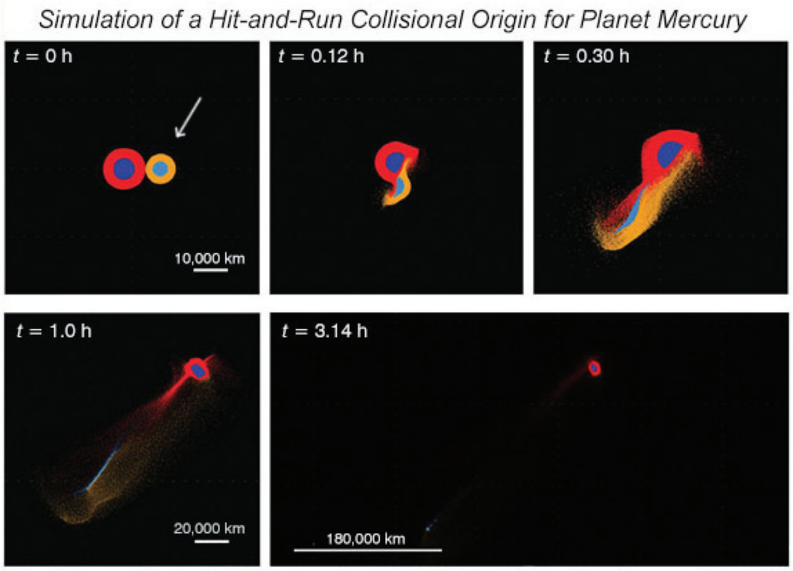


Figure 3. Numerical simulation of an oblique collision removes the outer silicate material from the impacted body, leaving behind a planet with a large iron core. Such a process may account for the present-day structure of Mercury.

lid versus mobile lid convection in the early Earth a problem bridging at least the geodynamics, geochemistry and mineral physics communities.

Overall the coupling between chemistry and physical processes remains poorly understood. Future work should focus on experimental and theoretical studies of the partitioning of volatiles between different reservoirs during Earth's formation. This will include developing experimental techniques to determine activity coefficients in multicomponent systems under the high temperatures and pressures of Earth's formation. Progress on understanding the observed chemistry of all of the terrestrial planets requires novel and technically challenging experiments.

Magma Ocean and Core Formation

Accomplishments

Abundances of moderately siderophile elements (like Ni and Co) in the bulk silicate Earth are conventionally interpreted as a time-integrated record of core formation. More recently, researchers have begun to measure isotopic fractionations in Si, Fe and other elements to provide additional constraints. The basic narrative of metal-silicate equilibration in a magma ocean is consistent with planetary growth by giant impacts because the energy released by accretion is more than sufficient to produce a largely molten mantle. Calculations for the lifetime of a magma ocean exhibit large differences (1 kyr to 100 Myr), depending on the assumptions made about radiative transport through the overlying atmosphere. Direct blackbody radiation to space promotes short cooling periods, whereas a thick proto-atmosphere can substantially extend the cooling time. This range of cooling times makes an important difference. The longer cooling times permit magma oceans to persist between large impacts. The cooling time can also dramatically affect the internal dynamics. Vigorous convection with velocities in the range of 10 m/s are possible with short cooling times. Such velocities are sufficient to impede settling of crystals and promote batch crystallization up to the point where the crystal content causes a rheological transition to solid-like behavior. Slow cooling and continuous sedimentation, on the other hand, may allow segregation of solids from liquids, yielding results closer to fractional crystallization. These processes affect the initial radial structure of the planet.

Unfortunately, the existing experimental data for partitioning of moderately siderophile elements between metal and silicate does not uniquely resolve major differences between competing accretion models (e.g., a simple single-stage scenario versus heterogeneous multi-stage scenarios). Advances in experimental capabilities using diamond-anvil cells have greatly extended the temperature and pressure conditions for studies on metal-silicate partitioning. Recent experiments reduce the need to extrapolate results to higher pressure and temperature. These results also point to the importance of major alloying elements in the metal (such as O and Si) because increases in their concentration at high temperature can affect the partitioning behavior of other trace elements. These results are changing our understanding of the average temperature, pressure and redox of the Earth during core formation. Early models for magma ocean dynamics and crystallization originated from studies of lunar samples and the recognition that rock types found on the Moon could be explained by evolution from a nearly-completely molten to a solid state. Similar models have been invoked for the early Earth, where high initial energy states may have led to an upper magma ocean, and a partially solid lower mantle. The consequences of such models may have been profound, leading to imperfect mixing of materials that ultimately formed the upper and lower mantles, and because of high-pressure and temperature, partitioning that may have occurred within the mantle, rather than at the core-mantle boundary interface.

The models of early Earth differentiation have profound implications for geochemistry, offering the possibility of deep mantle reservoirs separated early in Earth's evolution, possibly hosting primordial noble gases, or reservoirs with unique signatures of long-lived or extinct radionuclides. Equally, the imprint on geophysical models is also significant. The aftermath of early Earth magma oceans may have led to mantle stratification, or the preservation of partially molten regions of the mantle as a consequence of differentiation, as suggested for ultra-low velocity shear zones (ULVZs), or large low shear velocity provinces (LLSVPs). Existing problems in magma ocean dynamics remain regarding the time-scales of magma ocean processes, the crystallization dynamics permissible, and chemical fractionations that would be predicted during this major evolutionary process in the early Earth.

Future Directions

Progress in understanding magma ocean dynamics and the aftermath of giant impacts will require a better understanding of the phase diagram of mantle minerals and more reliable estimates of physical properties (such as the density of liquids and solids). Better computational models are also required to assess the extent of mixing in the interior following a giant impact. Some aspects of the dynamics may be similar to conditions encountered in the present-day core, where the influences of low viscosity and planetary rotation play an important role. Ongoing advances in geodynamo modeling are likely to have broader application to magma ocean dynamics.

Measurement and interpretation of short- and long-lived radioisotopes will provide key observations for establishing the nature and extent of primitive chemical anomalies in the early Earth. Along with these exciting developments, the use of geoneutrino detection may be important (see sidebar, page 18).

Additional work is also required in both natural and experimental studies of the highly siderophile elements (e.g., Ir, Pt). These elements are tracers par excellence of metal-silicate equilibrium, but their concentrations in the bulk silicate Earth have been interpreted to reflect late accretion components. Issues persist regarding the effect of high pressure/temperature partitioning of these elements at conditions relevant to Earth's lowermost mantle. Examining these issues and the overall distribution of highly and moderately siderophile elements and strongly chalcophile elements remains a major challenge for understanding core formation and early differentiation in Earth.

Core-mantle interactions—chemistry and dynamical consequences

The initial compositions of the core and the mantle are set by the process of metal-silicate differentiation. Concentrations of moderately siderophile elements in the mantle suggest that the bulk of core material last equilibrated with the silicate part of the Earth at conditions appropriate for a deep magma ocean. Subsequent chemical interactions between the core and the mantle are often thought to be severely limited because of slow diffusive transport through mantle minerals. However, several recent developments have drawn new attention to the possible role of chemical interactions.

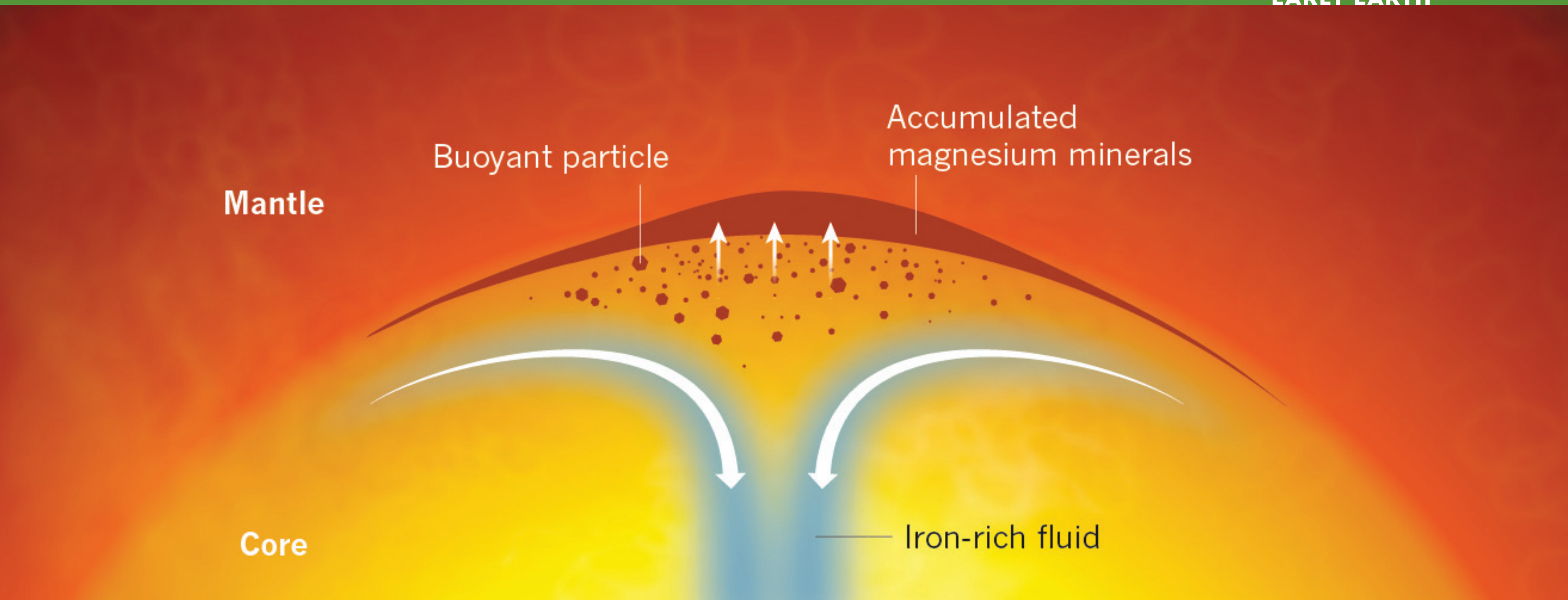


Figure 4. Exsolution of Mg-bearing minerals from the core may offer a new energy source for powering the geodynamo. Buoyant crystals rise to the top of the core, while a dense iron-rich liquid sinks into the interior. The fluid motion helps to maintain the geomagnetic field. From Buffett (2016).

Accomplishments

Advances in high-pressure and -temperature experiments suggest that the iron alloy in the core is substantially undersaturated in O and possibly Si relative to conditions expected at the core-mantle boundary. This disequilibrium should drive a transfer of O and/or Si to the core over geological time, although the rate of transfer could be quite slow. On the other hand, even small amounts of partial melt at the base of the mantle can dramatically enhance mass transfer to the core, particularly during the early evolution of the Earth. It is difficult to avoid some transfer of mass between the core and the mantle. In fact, the transfer may occur in both directions.

Theory and a growing number of experiments now suggest that normally insoluble elements, such as Mg, can dissolve into the core at sufficiently high temperature. These results raise the possibility of exsolving Mg-bearing oxides and silicates from the core with cooling. Such a process would offer a new source of compositional buoyancy in the core because the exsolved oxides and silicates would leave behind a residual liquid that is enriched in iron. This dense liquid would help to drive fluid motions in the core and may fulfill the energy needs for the geodynamo. The buoyant oxides and silicates would rise to the top of the core and gradually be incorporated into the mantle, although the ultimate fate of the precipitates depends on their density relative to mantle minerals.

Future Directions

New experiments and theory are required to better constrain the equilibrium between iron and silicate melt, particularly at high temperature. Refined estimates of iron-silicate equilibrium should be incorporated into geodynamic models (both core and mantle models) to quantify the fate and dynamical significance of core-mantle interactions. Special attention should be given to the distribution and origin of highly siderophile elements in the mantle because estimates of the mantle abundance over geological time provide a valuable constraint on both core-mantle evolution and accretion processes in the early Earth.

Early Environment and Onset of Plate Tectonics

Earth was substantially affected by core formation and mantle degassing during the earliest stages of its evolution. Both of these processes leave geochemical signatures of events that occurred within tens to a hundred million years of Earth's formation. The discovery of old (at least 3.8 billion years) crustal rocks and minerals (at least 4.4 billion years) on Earth now allows inferences on the state of Earth's surface and shallow interior within half a billion years or less of Earth formation.

Accomplishments

Perhaps one of the most surprising results revealed by these old crustal materials is that by 4.36 Ga, Earth's surface was cool enough to support the presence of liquid water, implying that within about 200 Ma of formation, at least the outer parts of the Earth had cooled to temperatures not dramatically different from those on the present Earth. Another, still debated, implication suggested by the data for these old rocks is that plate tectonics may already have been in operation on Earth by 4.3 to 4.4 Ga.

The timing of the onset of plate tectonics remains a major question in studies of Earth's interior. Studies of the limited outcrops of Earth's earliest rocks and minerals indicate conditions somewhat similar to today close to Earth's surface, perhaps indicating early onset of plate tectonics. Similarly, inclusions within diamonds indicate plate tectonics beginning earlier than 3.5 billion years ago. On the other hand, vestiges of Earth's early plate tectonics are generally lacking in the geological record and are limited. For example, slivers of Earth's oceanic crust that are obducted onto continents during collision, termed ophiolites, have only been definitively recognized as early as two billion years ago.

Future Directions

More realistic geodynamic models are required to quantify changes of tectonic behavior with mantle potential temperature. These models would allow predictions of the melt conditions and likely partial melting processes occurring in Earth. Similarly, further studies of early Earth materials and of ophiolites may be required. Early earth ophiolites may look very different from Proterozoic ophiolites. For example, some have argued that Archean greenstone belts in fact represent ancient ophiolites. If so, these terrains and the unusual rocks within them, such as komatiites, may require reappraisal.

Origin of the Earth's Inner Core and the Geodynamo

Accomplishments

A growing area of study is the link between the development of planetary interiors and habitability. The geodynamo is of special importance because it holds off the solar wind. Extreme solar winds, flares, and coronal mass ejections associated with the active young Sun have the potential to erode early planetary atmospheres. The presence or absence of the geodynamo and magnetosphere for the earliest Earth suggest quite different pathways for the evolution of the atmosphere and hydrosphere.

When and how did the geodynamo begin? Paleomagnetic evidence suggests that the Earth has possessed a magnetic field for the past 3.4 billion years or longer. Establishing whether a magnetic field was present at earlier times remains an important research question because the existence of a field provides a powerful constraint on the overall dynamics of the planet. A key factor is the vigor and style of convection in the mantle because it regulates the cooling of the core. The threshold for field generation in the core typically requires fluid velocities on the order of several km/year, but a more fundamental obstacle for the geodynamo is simply getting the core to convect. A pervasive magnetic field in the early Solar System would provide the necessary seed field, so the question of when the geodynamo began is ultimately tied to the onset of core convection and the history of the inner core.

The solid inner core began to form from the liquid core when Earth's central temperature dropped sufficiently to allow metal crystallization. Conventional estimates for the age of the inner core range from one to two billion years, based on thermal evolution models. In this conventional view, the geodynamo is sustained by a combination of thermal and compositional convection. Compositional convection is attributed to light alloying elements that are excluded from the inner core as it grows by solidification. Prior to the nucleation of the inner core, compositional convection would not operate and the geodynamo would have been driven solely by thermal convection. However, a recent revision of estimates for the thermal conductivity of iron alloys at high pressure and temperature has profoundly changed our estimates for the inner-core age (suggesting new values of 500 million years or even less), and has important consequences for energy sources available to drive the geodynamo.

A higher thermal conductivity increases the rate of conductive heat loss from the core, leading to greater heat transport by conduction. As a result, the energy available to drive the geodynamo is significantly reduced. In fact, current estimates for the thermal conductivity permit the conducted heat flow in a well-mixed core to exceed the heat flow into the base of the mantle. In this scenario, thermal convection is largely shut down and a layer of warm fluid is expected to accumulate at the top of the core. Convection in the core is maintained by compositional buoyancy associated with inner-core growth, but prior to the formation of the inner core there are insufficient energy sources to maintain the geodynamo.

Sustaining the high heat flow needed to generate the magnetic field by thermal convection alone may require unreasonably high initial temperatures in the core. There are two possible solutions. In light of alternative first principle calculations, it has been suggested that the recent high conductivity values may not be correct. Reverting to old estimates would permit more efficient thermal convection at lower heat flows. Alternatively, we need to invoke new energy sources for the geodynamo, particularly during early times. There is a growing effort to quantify tidal or precessional energy sources, as well as to identify new sources of compositional buoyancy, possibly due to exsolution of light alloying elements as the core cools. The latter option would imply mass transport between the core and the mantle with potential for testable geochemical consequences.

Simple expectations of monotonic changes in the core cooling rate might suggest a magnetic field in the present-day Earth would imply a magnetic field at all earlier times. However, several factors could confound this expectation. For example, the onset of plate tectonics is potentially important because recycling the cold thermal boundary layer in this style of convection is very effective at cooling the interior and drawing heat from the core. Conversely, an accumulation of radiogenic material at the base of the mantle could suppress core cooling, particularly at early times when the rates of radiogenic heat production were higher. Release of latent heat from a solidifying basal magma ocean could have a similar effect.

Another important factor is the initial thermal and compositional state of the core. Giant impacts do not disperse energy uniformly through the interior of the target. The highest temperatures in numerical simulations are often produced at the top of the core, which implies thermal stratification at early times and no geodynamo. Similarly, the initial compositional state might inhibit an early geodynamo. The abundance of light alloying elements in the cores of impacting bodies is expected to increase with the size of the body (due to the associated effects on pressure and temperature). Early impacts from smaller bodies would deliver core material that is enriched in iron relative to later (and larger) impacts. While the accretion process is liable to have a complex history with uncertain consequences for the initial thermal and compositional states in the core, it is at least possible that convection and magnetic-field generation was not possible until the core was mixed by subsequent cooling or other processes.

Future Directions

Observational constraints on the onset of the geodynamo would offer valuable insights into the time of a wide range of early processes. The magnetization of zircons offers a tantalizing hint that the geodynamo may be more than 4 billion years old, comparable in age to the ancient dynamos of Mercury and Mars. Continued studies are needed to further assess the fidelity of the zircon magnetizations and explore the first billion years of geodynamo history. A better characterization of the Earth's initial state would afford greater confidence in assessing the likelihood of convection in the core during the first billion years of evolution. Future process will require an integrated approach that combines modeling studies, geochemical constraints on the earliest state and paleomagnetic evidence of an ancient field.

GEONEUTRINOS

The Earth's heat flow is 46 ± 3 TW (10^{12} watts), a number that has been firmly established for the last four decades. There is now vigorous debate regarding what fraction of this power comes from primordial versus radioactive sources. This debate touches on the composition of the Earth, the question of chemical layering in the mantle, the nature of mantle convection, the energy to drive Plate Tectonics, and the power source of the geodynamo, which produces the magnetosphere that shields the Earth from the harmful cosmic ray flux.

Starting in 2005 particle physicists began detecting the Earth's geoneutrino flux, the planetary emission of electron anti-neutrinos that are derived from naturally occurring, radioactive beta-decay events inside the Earth. Neutrinos and their anti-matter counterparts are near massless and uncharged elementary particles, which travel at close to the speed of light. The Earth is mostly transparent to these elusive messengers that reveal the sources of heat inside the Earth as they virtually escape detection, with the globally averaged flux being ~6 million per centimeter squared per second. However, detecting this flux is a significant challenge (detector efficiencies are order 10^{-20}) and only a few events per year are detected from thorium and uranium sources inside the planet. This meager dataset, however, allows determination of the amount of radiogenic power driving the Earth's engine.

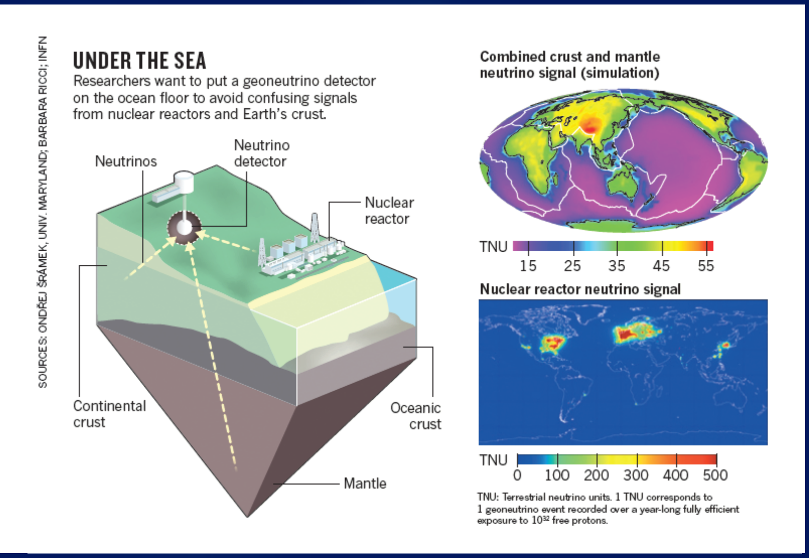


Figure from Witze (2013)

Geoneutrino detectors open the possibility of directly measuring the amount of Th & U in the Earth. These elements, along with K, account for more than 99% of Earth's radiogenic heat production and together with the primordial energy of accretion and core segregation define the total planetary power budget of the planet. By defining the absolute abundance of Th & U in the Earth, with accuracy and precision, we can

1. define the building blocks, the chondrites, that formed the Earth,
2. resolve ever vexing paradoxes (e.g. 4He-heat flow, Ar budget and degassing) that fuel the debates of compositionally layered mantle structures or not,
3. discriminate among models of mantle convection that define the thermal evolution (dT/dt) of the Earth,
4. potentially identify and characterize any deep hidden geochemical reservoirs (or not) in the mantle, and
5. examine the distribution of Th and U in the Earth between the crust and mantle.

Moreover, such studies can put to rest marginal hypotheses that portend the existence of georeactors in or near the Earth's core.

All present geoneutrino detectors are sited on continental crust. These detectors need to see through the continental crust (a Th and U rich layer) to determine how much Th and U is in the mantle. Uncertainties in models of the Earth (including those for the continental crust) and the present sensitivity of instruments used to detect geo-neutrinos means that we are not yet capable of seeing the mantle signal; the size of the mantle signal is presently equal to the uncertainty in detection. Proposed ocean-based detectors would receive most of their signal from the mantle, opening possibilities of mapping out deep-seated structures, potentially as deep as the core-mantle boundary, and allowing tests of the questions outlined above.

IV. DEEP EARTH ENGINE

Within the deep Earth there are two distinct but interconnected heat engines distinguished by their locations, compositions, and dynamics. The highly viscous silicate mantle and predominantly iron core interact through the core-mantle boundary, a region of considerable complexity and interest. As already discussed, the Earth's thermal regime is linked to its composition, the degree of chemical layering in the mantle, the nature of mantle convection, the energy source for plate tectonics, and the power source of the geodynamo. Several important issues related to the present-day deep Earth engine have already been touched on in the Early Earth theme, including core conductivity, the composition and distribution of light elements in the core, and the inventory and distribution of radiogenic elements within the deep Earth (see neutrino sidebar). Earth's evolution from the beginning has determined its present state. Here we focus on the integration of multiple disciplinary tools to study that state, but necessarily including a temporal perspective of tens to hundreds of million years to understand the patterns of flow and material transport in the mantle and its interactions with the core (Figure 5). We begin with the mantle, moving downward through the core-mantle boundary region to the heat engine in the core. This also sets the stage for the third theme on Deep Earth to Surface Interactions.

The Mantle

The present-day structure and dynamics of the Earth's mantle represents a key target for CSEDI investigations, as an understanding of mantle processes requires constraints from seismology, geodynamics, mineral physics, petrology, paleomagnetism, and geochemistry, and an integration of experimental, computational, observational, and field-based approaches. A complete discussion of progress made in understanding the mantle over the past ten years is beyond the scope of this report; here we focus on the themes of understanding patterns of mantle flow and transport, as well as understanding the origin and evolution of the large low shear velocity provinces (LLSVPs) that dominate the structure of the lower mantle.

Accomplishments

The past decade has seen a number of advances:

- **Development of new techniques (e.g., adjoint simulations) for modeling mantle flow**
- **Observations of seismic anisotropy in the deep mantle (transition zone, uppermost lower mantle, and D")**
- **Observations of stagnant slabs in the mid-mantle (~1000 km)**

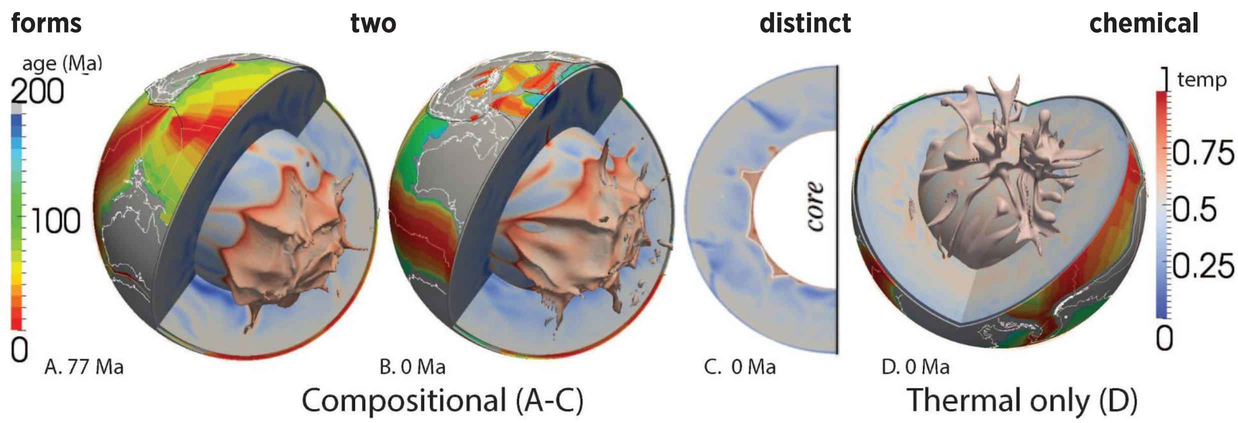


Figure 5. Four-dimensional dynamic Earth model from 200 Ma shown at 77 Ma (A) and the present (B) as viewed over the south Pacific. The model incorporates continuous evolution of surface plates while assimilating the age distribution of oceanic plates (color coded on top surface), thermal structure of slabs in the upper 200 km, plate boundaries and plate velocities from GPlates. A high-density chemical layer in the deep mantle piles beneath the Pacific and Africa. A 2D cross-section shows the compositionally distinct structure on the CMB beneath the Pacific (C). Considering only the thermal effects (D), the model would predict a field of plumes under the present day Central Pacific. Modified from Bower et al. (2013).

- **Improvements in mantle tomography methods and models (e.g., full wavefield) that hint at complex, "hybrid" modes of mantle convection**
- **Dynamical models that successfully reproduce some first-order aspects of LLSVP structure**
- **Seismic imaging of LLSVPs and first-order agreement among different tomography models as to their locations**
- **Observations of correlations between deep mantle shear wave structure and surface manifestations (e.g. large igneous provinces, geochemical signatures)**

The pattern of flow in the Earth's mantle, how that pattern has evolved over time, and the extent of mixing between upper and lower mantle reservoirs represent key problems in the study of Earth's interior dynamics, and were a major focus of the last CSEDI report. Improved understanding of the pattern of flow of the mantle has been informed by new numerical models of flow, including adjoint approaches, and leveraging of new computational approaches and resources, such as those provided under the Computational Infrastructure for Geodynamics (see infrastructure section). Increasingly, these simulations of mantle flow incorporate reconstructed plate motions and seafloor age data as constraints (see Figure 5 for a simulation spanning the past 200 My); models such as these assimilate a broad spectrum of observations to provide forward predictions of mantle structure as well as surface observables such as topographic and sea level change, heat flux, and surface volcanism, and are able to produce plausible structures like the thermo-chemical piles or LLSVPs in the deep mantle that have been imaged using seismological techniques.

Analyses of seismic data have provided important contributions over the past decade through new observations of seismic anisotropy in the deep mantle over a range of depths and scales. Seismic anisotropy is routinely measured in the upper mantle and exploited as a constraint on mantle deformation processes and history, but observations in the deep mantle are considerably more challenging. Recent work has provided convincing evidence of both radial and azimuthal anisotropy in the mid-mantle (transition zone and uppermost lower mantle; see example in Figure 6), while new observations of anisotropy at the base of the mantle provide tighter constraints on the geometry of anisotropy and how anisotropic structure varies over small length scales.

Tomographic images of present-day mantle structure have now advanced so that it is possible to infer patterns of mantle flow, including both downwelling slabs and upwelling plumes. It has been understood for some time that some slabs appear to stagnate in the mid-mantle, perhaps due to the effects of trench migration, the transition zone phase discontinuities, an increase in mantle viscosity at mid-mantle depths, or a combination of these effects. However, recent tomographic images have made it clear that many subducting slabs stagnate not at a depth of 660 km, but at approximately 1000 km, considerably deeper than the base of the transition zone. More generally, advances in mantle tomographic imaging techniques (particularly the use of finite-frequency or full-waveform approaches) have made it increasingly clear that both upwellings and downwellings interact with mantle structure in a complex way,

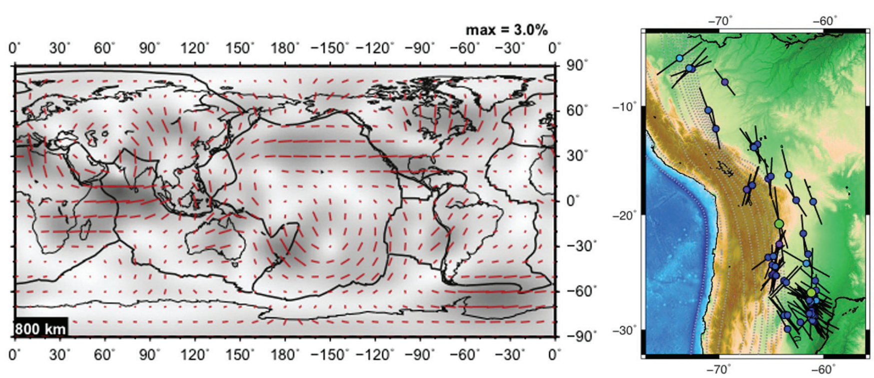


Figure 6. Recent global (left) and regional (right) observations of seismic anisotropy in the uppermost lower mantle. Left panel: Global 3-D azimuthal anisotropy model at a depth of 800km. Red bars represent fast direction of vertically polarized shear-waves and their length is proportional to the amplitude of the anisotropy, which is also indicated by the background gray scale. Plate boundaries and continents are shown by black lines. From Yuan and Beghein (2013). Right panel: Source-side shear wave splitting observations for deep (transition zone depth) earthquakes in the South America subduction zone, recorded at distant stations and corrected for the effect of anisotropy beneath the receivers. Bars indicate the fast splitting direction for each measurement, projected along the raypath to a depth of 800km. From Lynner and Long (2015).

providing a snapshot of present-day mantle flow that is complex and departs considerably from simple end-member models (such as layered versus whole-mantle convection).

Tomographic models of seismic shear velocity of the lowermost mantle are dominated by two large, roughly antipodal structures with reduced V_s, known as the Pacific and African LLSVPs. Normal mode seismology indicates that the LLSVPs are likely high density, and lack of correlation between *P* and *S* wave velocities has been invoked as evidence for chemical variations. Spatial correlations have been noted between LLSVPs and other structures such as ultra low velocity zones (ULVZs are thin anomalous areas found at the very base of the mantle.). The edges of LLSVPs are also associated with strong seismic anisotropy in the lowermost mantle and may correspond to surface expressions of volcanism such as hotspots and large igneous provinces (LIPs). Over the past decade, considerable effort has been devoted to studying LLSVPs and their interactions with the rest of the mantle have been documented.

Geodynamical modeling of LLSVP-like structures has been carried out, using both two-dimensional and fully three-dimensional approaches. Relatively realistic numerical models of mantle thermochemical structure that take into account the history of subduction of differentiated oceanic crust back into the mantle are able to match many aspects of the geometry and properties of LLSVPs, as inferred from seismology (e.g., Figure 5). These models have been enabled by advances in computational approaches and infrastructure, but a key aspect is the incorporation of constraints from mineral physics and past plate motions into geodynamical simulations.

Our ability to image structures in the lower mantle, particularly LLSVPs, has improved drastically over the past decade. Progress has come on several fronts: first, it is clear that different research groups implementing tomographic imaging for lower mantle Vs structure are beginning to achieve some consensus on the existence, location, size, shape, and strength of the LLSVPs anomalies, although the details remain different among different models. Second, the implementation of new imaging techniques that take advantage of the whole wavefield (rather than just traveltime observations) are yielding ever more detailed pictures of the velocity structure of the mantle, illuminating both the LLSVPs themselves and their spatial relationships with upwelling features in the shallower mantle. For example, recent images (Figure 8) demonstrate the existence of plume-like upwellings beneath major Pacific hotspots that appear to originate within the Pacific LLSVP structure at the base of the mantle. In addition to improved imaging of isotropic seismic structure, there is convincing evidence that the edges of LLSVPs are associated with particularly strong anisotropy in the D" region at the base of the mantle.

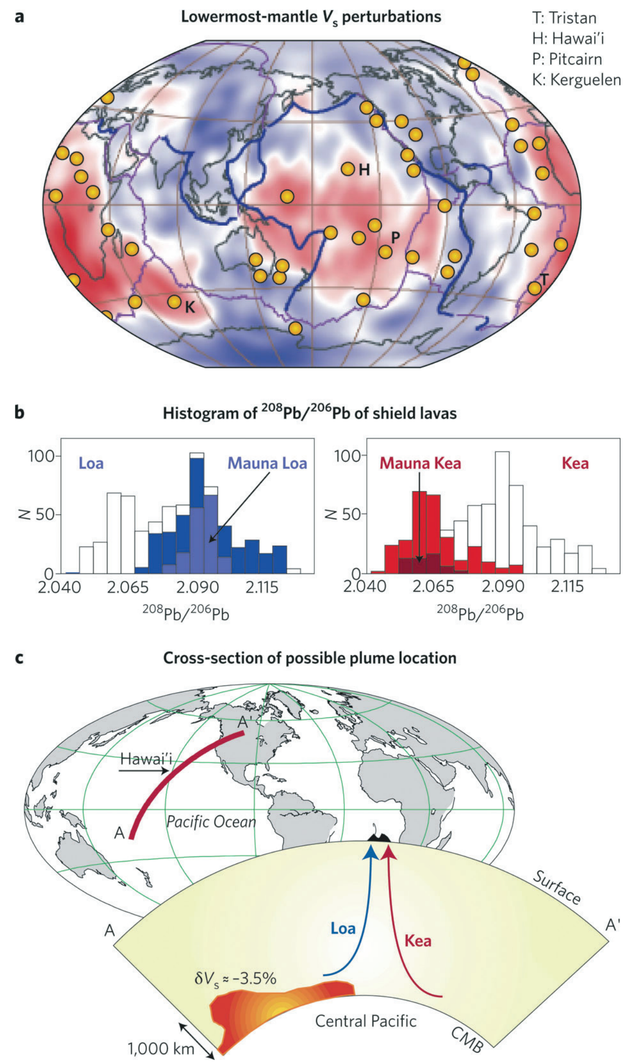


Figure 7. (a) Global map of lowermost mantle Vs perturbations, with the Pacific "Ring of Fire" outlined with thick blue lines, and hotspot locations shown with yellow circles. Hawaii is marked with "H." (b) Histogram of $^{208}Pb/^{206}Pb$ for Hawaiian shield lavas, showing clear distinctions between the Mauna Kea and Mauna Loa groups. (c) Cross-section through the Hawaiian mantle plume down to the CMB, showing a schematic representation of the low-velocity structures beneath the central Pacific. Hawaiian Island surface locations and relative portion of the Loa and Kea trends in the mantle plume are indicated. From Weis et al. (2011).

Another exciting development has been the discovery and exploration of potential correlations between the locations of LLSVP material in the lowermost mantle and surface observations, such as hotspot locations, LIP eruptions, and geochemical characteristics of erupted magmas. The apparent spatial correlation between LLSVP edges and hotspot volcanism was pointed out about a decade ago, leading to the suggestion that the edges of LLSVPs may represent plume generation zones. While there has been controversy about whether surface features correlate better with LLSVP edges or their interiors, the investigation of apparent correlations between lowermost mantle structures and surface observables, including geochemistry, is proving fruitful. For example Figure 7 presents work showing that the compositional asymmetry of the Hawaiian volcanic chain could be explained by sampling of material on either side of the Pacific LLSVP edge by a deep mantle plume.

Future Directions:

- **Robust imaging of mantle plumes.**
- **Understanding mechanisms and implications of seismic anisotropy in the deep mantle.**
- **Constraining the rheology of the deep mantle and exploring the implications for mantle dynamics.**
- **Understanding links between deep mantle dynamics and surface manifestations such as volcanism, subduction initiation, and plate tectonics more generally.**
- **Understanding the relative contributions of thermal versus compositional heterogeneity to LLSVP structure.**
- **Understanding the origin of LLSVPs and how have they evolved through time.**
- **Evaluating the implications of LLSVPs for the geochemical evolution of the mantle.**
- **Understanding whether and how LLSVPs express themselves in surface processes.**
- **Understanding the potential implications of lower mantle spin transitions on mantle dynamics.**

There is much that we still do not know about patterns of mantle convection and the origins of LLSVPs, but there is considerable hope for advances in the near future. Seismic tomography holds potential for greatly enhanced and robust imaging of current mantle plumes. A multidisciplinary approach to understanding anisotropic seismic structure and its origin can expose the nature of deformation that led to our images of the current state. The rheology of the deep mantle remains poorly constrained, and is important in parametrization of models for mantle dynamics. All of these are important controls on the links between the surface and deep interior elaborated in Theme III.

A major goal for CSEDI efforts going forward is one that has so far proved elusive: the robust imaging and interpretation of upwelling plumes in the mantle. There has been vigorous debate over the nature, size, shape, origin, and dynamic behavior of mantle plumes over the past several decades, but recent advances in tomographic imaging techniques hold promise for a great leap forward in our understanding of mantle upwelling behavior. For example, recent waveform tomographic images such as the one shown in Figure 8 reveal a variety of plume morphologies, with inferred plume conduits that have relatively large dimensions and seem to

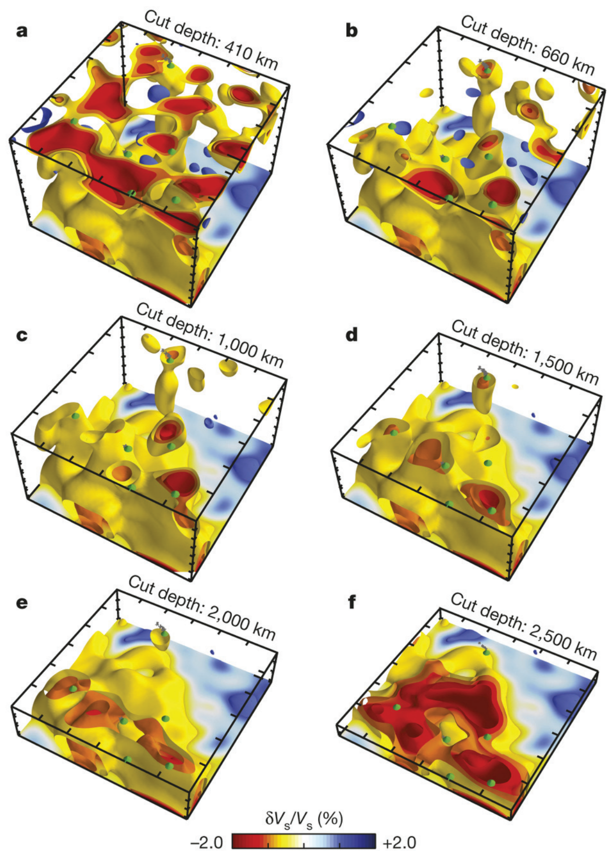


Figure 8. Shear wave velocity perturbations at different depths beneath the Pacific Superswell, shown with respect to the global average at each depth. Green cones in each box indicate the locations of major Pacific hotspots, projected down from the surface. In box (f), at a depth of 2500 km, patches of much lower-than-average velocity start appearing within the Pacific LLSVP, continuing down to the core-mantle boundary. From French & Romanowicz (2015).

merge and diverge at different mantle depths. With rapid advances in the theoretical and computational underpinnings of waveform tomography, the CSEDI community is poised to make rapid progress on the problem of imaging plumes. The interpretation of mantle tomographic images will necessarily be a cross-disciplinary enterprise requiring incorporation of constraints provided from geochemical observations, and experimental mineral physics (see sidebar, page 30) in addition to geodynamic modeling.

Another immediate goal for CSEDI is an understanding of mechanisms and implications of seismic anisotropy in the deep mantle. Because anisotropy results from mantle deformation (integrated over time), it provides an invaluable complement to observations of isotropic structure, which must be interpreted as a snapshot of the present-day mantle system. Recent observations of anisotropy in the deep mantle (transition zone, uppermost lower mantle, and the D" layer at the base of the mantle) are tantalizing, but major gaps remain in our understanding of how to interpret anisotropy in the deep mantle in terms of flow geometry. In particular, better constraints are needed on both single-crystal elasticity and dominant slip systems for deep mantle minerals, as well as on the presence and possible configurations of partial melt and other materials with contrasting elastic properties that might form SPO (shape preferred orientation) anisotropy. Furthermore, in order to fully exploit observations of deep mantle anisotropy to constrain flow patterns, a truly multidisciplinary approach (enabled by the collaborative CSEDI program) that integrates seismic observations, geodynamic models, and mineral physics observations is critical.

While recent advances in our understanding of mantle rheology have been made, the rheology of the mantle (particularly the deep mantle) remains one of the fundamental unsolved problems related to deep Earth dynamics, and this represents a prime target for CSEDI research over the next decade. Computational and theoretical advances have enabled a new generation of geodynamic models of mantle processes, but major uncertainties in the parameters that go into these models remain, particularly rheological parameters. As with many aspects of deep Earth research, new constraints on deep mantle rheology (and its implications) will require input and synthesis across a range of disciplines, including laboratory experiments, geodynamic models, and the interpretation of seismic observations. A recent example of such a multidisciplinary approach proposed a sharp increase in viscosity at mid-mantle depths (~1000 km) from analysis of the geoid, a whole-mantle tomographic model, and numerical simulations of mantle convection With continued development of approaches such as this, the CSEDI community is poised for new discoveries in the realm of deep mantle rheology.

Another major goal for CSEDI over the next decade is the exploration of links between mantle flow patterns and surface manifestations of mantle processes such as hotspot volcanism and, more fundamentally, plate tectonic features such as plate boundaries. Plate tectonics is the surface expression of mantle convection, but links between patterns of flow associated with the mantle's convective system and surface plate tectonic features such as subduction zones remain to be elucidated in full. Fundamental aspects of plate tectonics, such as the mechanisms and feedbacks of strain localization at plate boundaries and the processes by which subduction zones initiate, remain poorly understood, and a complete understanding of these processes is necessarily tied to how the underlying mantle behaves as a dynamic system (these questions are also explored under Theme III).

A crucial goal of deep Earth research over the next decade will be to understand to what extent the LLSVPs represent thermal versus compositional heterogeneity, and what the source of this heterogeneity is. While a number of studies have argued that the LLSVPs cannot be purely thermal in origin, it is unclear to what extent compositional heterogeneity is required by the data, and some recent work has argued that a purely thermal origin can perhaps be reconciled with observations. The extent to which the LLSVP anomalies are chemical versus thermal in origin is a critical piece of the puzzle to understand their origin and evolution through time, which represents another key goal in the study of LLSVPs. Do LLSVPs represent structures "frozen in" early in Earth's history from the magma ocean, or are they dynamic and changing structures that are maintained by mantle convection and the continuous addition of chemically distinct material via the process of subduction? Do the LLSVPs remain relatively fixed in the deep mantle over Earth time, or are they transient structures whose form, location, and properties change? Are mesoscale structures such as the so-called Perm Anomaly similar to the larger LLSVPs in terms of their composition and origin? As major structures of interest in the Earth's lower mantle, LLSVPs provide a specific target for imaging studies and for interdisciplinary investigations into fundamental questions about Earth's interior dynamics, such as whether mantle processes are controlled from the top down (by plate tectonic processes at the surface) or from the bottom up (by deep structures such as LLSVPs).

More broadly, the geochemical implications of LLSVPs remain a frontier area of exploration, with a number of fundamental unanswered questions about the role that deep mantle reservoirs play in geochemical cycling in the deep Earth. For example, might LLSVPs represent a "hidden reservoir" of material that does not generally participate in mantle circulation unless it is sampled by mantle plumes, thus explaining the different chemical signatures of mid-ocean ridge and ocean island basalts? Can the chemical variations observed both within and between different hotspot trends be attributed to differential sampling of LLSVP material? Spatial correlations between geochemical components and deep mantle structure are only just beginning to be explored, and the question of whether and how chemically distinct reservoirs can persist within a realistically convecting mantle is critically important, and requires constraints not only from geochemistry but also from geodynamical modeling and seismic imaging.

While geochemistry represents one potential target for interrogating the connections between surface observations and deep mantle structure, there are a host of unanswered questions about how surface features relate to deep mantle structures such as LLSVPs; these present a concrete goal for the next decade of CSEDI research. For example, how significant are the apparent (and often qualitative) correlations between LLSVPs (and more specifically their edges) and hotspot volcanism? Should we expect such correlations in a vigorously convecting mantle, which might lead to, for example, tilted plume conduits? What are the relationships between plate tectonic features at the surface, such as the locations of ridges and subduction zones, and lowermost mantle structures such as LLSVPs? What is the role of downwellings (i.e., subducting slabs), if any, in maintaining LLSVPs and other lowermost mantle structures?

Finally, the discovery of pressure driven electronic spin transitions in all of the major iron-bearing lower-mantle phases (ferropericlase, bridgmanite, and silicate post-perovskite) has sparked intense activity among mineral physicists during the past decade and provided a host of new frontiers for future investigation. Mineral physics experiments and calculations indicate that spin transitions cause dramatic changes in density, elasticity, chemical diffusivity, and electrical conductivity as well as partitioning of iron between the minerals, and between various crystallographic sites in a mineral. Unambiguous anomalous elastic behavior has yet to be detected in seismological observations, from which one might expect unusual velocity gradients, but spin transitions have been invoked as potential explanations for chemical heterogeneity in the mantle. Understanding the potential impact of spin transitions in our planet's deep interior requires collaboration with the geophysics, geodynamics, and geochemistry communities. This includes incorporating spin transitions and other results from mineral physics more broadly into modeling of lower-mantle anisotropy and D" structure, core-mantle interactions and heat transfer through the lower mantle, and global chemical geodynamics (Fig. 9).

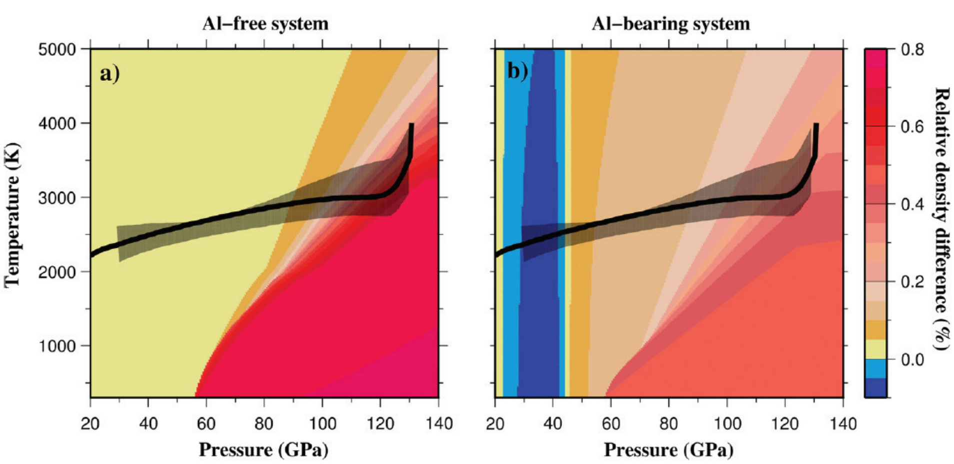


Figure. 9. Relative density difference (%) between models with and without spin state transition, as a function of pressure and temperature, for (a) Al-free, and (b) Al-bearing compositions. The black line is a proposed geotherm, and the shaded gray area corresponds to the range of possible lower mantle temperatures inferred from seismic models combined with experimental mineralogy data (from Vilella et al., 2015).

The Core-Mantle Boundary Region

The core-mantle boundary region, or CMB, encompasses the lowermost few hundred km of the mantle along with the top of the vigorously convecting outer core. This boundary, where crystalline silicate and oxide meets the molten iron outer core, is among our planet's most structurally complex regions and displays the largest contrast in physical and chemical properties of all the regions in the Earth. The D" region, the deepest few hundred km of the mantle, has attracted particular scrutiny from deep Earth researchers. Although it is a relatively thin layer, it seems to be the key to understanding core-mantle interactions and plays a pivotal role in global dynamics and evolution. The CMB is a particularly important scientific target for CSEDI, with a number of notable recent accomplishments and a number of outstanding questions that represent frontier areas for the next decade.

Accomplishments:

- **Discovery and characterization of the post-perovskite phase transition and correlation with the D" seismic discontinuity.**
- **Characterization of structural heterogeneity at the top of the outer core and outer core stratification.**
- **Initial estimates of heat flux across the CMB using post-perovskite stability**
- **Seismic characterization of ultra-low velocity zones (ULVZs) and mesoscale structures such as the Perm Anomaly.**

The past decade has seen a number of major findings in mineral physics related to the CMB, none as important as the "post-perovskite" (ppv) phase, discovered in 2004, that is stable at the extremely high pressures and temperatures that exist near the core-mantle boundary. This discovery galvanized a flurry of research activity across the fields of geodynamics, geochemistry, seismology, and the high-pressure geosciences community. This phase may explain the long-enigmatic discontinuity in seismic wave velocities at the top of the D" layer. Additionally, the crystal structure of this phase could explain the seismic anisotropy observed within D". The possible presence of ppv provides constraints on the possible heat flow out of the core (and thus the driving force for the geodynamo), as well as produce new paradigms for how mantle plumes might form in the lowermost mantle.

In particular, the suggestion that there might be a double crossing of the post-perovskite stability field in some regions of D", depending on the regional geotherm, opened up the exciting possibility of a relatively direct observation of heat flux at the base of the mantle. This model invokes a transition to ppv at the top of the D" layer, with an additional transition from ppv to bridgmanite close to the base of the mantle, as proximity to the outer core leads to high temperatures outside the ppv stability field (Figure 10). While a number of assumptions must be made in order to carry out such a calculation (e.g. the geotherm, the Clapeyron slope of the phase transition), this strategy provides a compelling opportunity to exploit observations of seismic discontinuities to learn about the Earth's thermal structure.

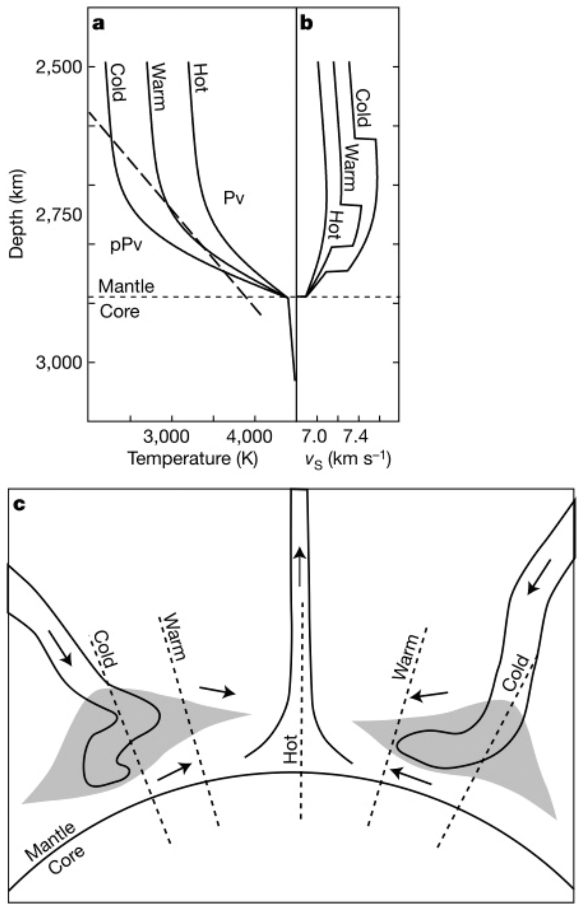


Figure 10. Illustration of the post-perovskite double crossing model and how it can be used to constrain lower mantle heat flux. Shown are the relationship between three schematic geotherms and the ppv phase boundary (a), corresponding shear velocity profiles (b), and a sketch of possible lower-mantle structures (c). In (c), the ppv layer is shown in light gray, schematic flow directions are indicated by arrows, and several examples of warm, cold, and hot mantle profiles are shown with dotted lines. From Hernlund et al. (2005).

Ultra-low velocity zones (ULVZs) are thin, localized regions at the very base of the mantle that involve sharp reductions in seismic velocity of ~10-30%, with reductions in S velocity generally being more dramatic than those in P velocity. There appear to be some tentative spatial correlations between ULVZs and both hotspots and the edges of LLSVPs, although only a few regions of D" have been investigated in detail for the presence of absence or ULVZs. Progress on the study of ULVZs has come on several fronts, including new observations that have taken advantage of the increasing availability of data from denser and wider-aperture seismic arrays, such as the EarthScope USArray. There has also been progress in the experimental investigation of possible explanations for ULVZ, including both those models that invoke the presence of partial melt and those that invoke a solid-state model of localized iron enrichment, which can simultaneously increase density and decrease seismic velocities.

Future Directions:

- **Understanding the origin and evolution of ULVZs and mesoscale structures**
- **More complete understanding of the post-perovskite stability field and the properties and distribution of post-perovskite at the base of the mantle.**
- **Accurate estimates of heat flux across the CMB.**
- **Understanding of melt properties (e.g. velocity, density) and behavior (e.g. presence, configuration, dynamic stability) at the base of the mantle.**

Although a great deal of progress has been made in our understanding of the core-mantle boundary region, major uncertainties remain, and there are several obvious areas of inquiry for CSEDI which are likely to yield fruit over the next decade. Building on the exciting discoveries related to post-perovskite (ppv) over the past several years will be important; in particular, we must place tighter constraints on the behavior of the ppv phase transition and how it depends on pressure, temperature, and composition. It is increasingly clear that the transition might not occur in relatively warm regions, leading to the juxtaposition of bridgmanite and cooler post-perovskite, but the precise conditions under which ppv is likely to be stable need to be delineated. Furthermore, more accurate estimates of heat flux across the CMB based on the stability field of post-perovskite are needed. The possibility of obtaining relatively direct constraints on the thermal structure of the deep mantle has been an exciting recent development, but a number of assumptions are made in these calculations, leading to a large range of estimated heat flux values (and errors on such estimates). Tighter constraints on the properties of the phase transition, such as its Clapeyron slope, will lead to a deeper understanding of lower mantle thermal structure.

Another area that is ripe for future progress is the investigation of melting behavior in the deep Earth, and the properties and stability of melts in the D" layer. Partial melts may provide an explanation for seismic observations such as ULVZs and D" anisotropy, but from a geodynamical point of view, there are major questions about their stability over time. Furthermore, alternative explanations for seismic observations that do not require melting have been proposed. Understanding whether partial melt is indeed present at the base of the mantle, the conditions (temperature, pressure, composition) at which melting can be expected, and the properties and dynamic stability of melts near the CMB will be a critical area of research for CSEDI going forward.

More generally, recent and future directions in the study of the CMB remind us that progress in deep Earth research depends on the synergy between different disciplines. For example, unusual observations from seismology may turn out to be highly revealing when matched with observations in the laboratory or from calculations and models or vice versa. The implications for very recent discoveries like the new silicate H-phase or tetrahedrally (and perhaps even octahedrally) coordinated carbonates are still not known, but these findings promise that the next decade will continue to produce exciting discoveries at the interdisciplinary intersection of deep Earth studies.

The Core

As the most remote and inaccessible region of the Earth's interior, the core is difficult to study, but it plays a crucial role in controlling the planet's thermal evolution and in generating its magnetic field. Accomplishments in understanding the core over the past decade of CSEDI have been driven by observational (e.g. seismic and magnetic field observations), experimental (e.g. high pressure mineral physics), and modeling (e.g. laboratory and computational geodynamo models) approaches.

Accomplishments:

- **Newly established phase diagrams for core materials.**
- **Better characterization of inner core anisotropy and heterogeneity.**
- **Advances in numerical geodynamical models and wider availability of code.**
- **Establishment of links between geodynamo model predictions and paleomagnetic and historical observations.**
- **New satellite-based geomagnetic observations (e.g. Swarm, CHAMP, Orsted)**

Improvements in observations and modeling in the past few years have combined to produce a number of important advances. Seismological observations of inner core structure (from both body waves and normal models) now reveal a complex spatial pattern of elastic anisotropy. Early studies appealed to a uniform distribution of preferentially aligned iron crystals to explain a relatively sparse data set. Rapid growth in the quality and quantity of observations has begun to illuminate a staggering degree of complexity. There is evidence for strong and sometimes abrupt changes in elastic properties with longitude. There are also suggestions that high attenuation of seismic waves occurs in regions where the wave speeds are fastest—counter to expectations for most mechanisms of intrinsic dissipation. Current interpretations favor the effects of scattering as the principal cause of seismic attenuation. There is little evidence of anisotropy in the uppermost region of the inner core and further suggestions that the innermost inner core has a distinct anisotropy, which appears to be tilted with respect to the anisotropy in the rest of the inner core.

Efforts to explain the origin of inner-core anisotropy have generally appealed to deformation processes because the effects of solidification should be expressed in a preferred orientation at the top of the inner core, where there is little evidence for anisotropy. Proposed explanations for inner-core anisotropy abound, but none, so far, is able to account for the observed complexity. Suggestions include the effects of thermal convection, magnetic stresses, and differential growth of the inner core. A recent and intriguing suggestion of inner-core translation (a form of thermal

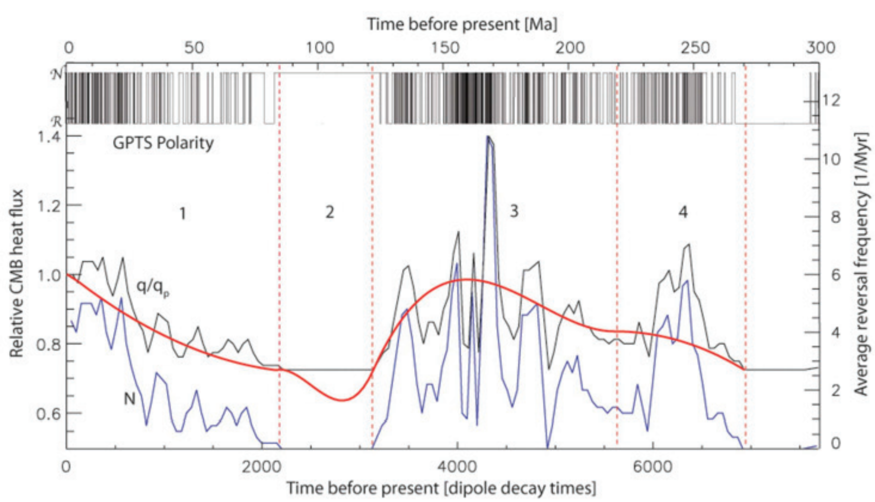


Figure 11. Core-mantle boundary heat flux variations versus time before present in Ma(top scale) and dipole decay times (bottom) derived from geomagnetic polarity reversal variations. Bar code shows polarity reversal record, with N normal and R reversed polarity. Blue curve is average reversal rate; Black give raw relative heat flux variation; red is smooth modeled variation with time (Olson and Amit, 2015).

convection) now appears less likely in the light of the high thermal conductivity of iron; strong thermal stratification is expected with high thermal conductivity, which suppresses all forms of thermal convection.

Advances in computational capabilities, along with better algorithms, have driven substantial progress in numerical simulations of the geodynamo. A growing collection of numerical results now offer valuable insights into well-observed features of Earth's magnetic field. Properties such as the strength of the dipole or the persistence of high-latitude patches of magnetic flux have been investigated and quantified using numerical models. Even the factors that control the frequency of magnetic polarity reversals have been assessed within the parameter regime that is accessible on modern computers (Figure 11). Recent advances in the implementation of parallel algorithms have opened the possibility of running much larger calculations on the world's largest computers. Numerical simulations running on hundreds of thousands of cores will greatly extend the accessible parameter regime.

Despite current limitations, the numerical models have been remarkably successful. It is possible to achieve realistic looking magnetic fields with fluid velocities that are comparable to estimates inferred from time variations in the magnetic field. This success has motivated a number of researchers to integrate numerical models with historical and/or paleomagnetic observations of the magnetic field. Efforts to develop data assimilation capabilities in numerical geodynamo models have shown great promise and are now used to make short-term forecasts. Much of this effort leverages existing capabilities in the field of numerical weather prediction but there are many new challenges that are unique to the forecasting of magnetic fields.

One motivation for the growing interest in data assimilation is the recent emergence of new satellite observations of the Earth's magnetic field through the Swarm, CHAMP and Orsted missions. These observations provide unprecedented spatial and temporal coverage, opening opportunities for new types of investigations. Greater integration of observations and models is a trend that is likely to continue into the future.

Future Directions:

- **Understanding core composition and the concentration of light element(s).**
- **Understanding the origin of inner core anisotropy and heterogeneity and links to growth mechanisms.**
- **Incorporation of more realistic physics (e.g. turbulence) into geodynamo models.**
- **Exploration of the implications of new estimates of high core thermal conductivity.**
- **Investigations of inner core/outer core coupling on geologic timescales.**
- **Characterization and interpretation of outer core stratification.**
- **The path to geomagnetic prediction**

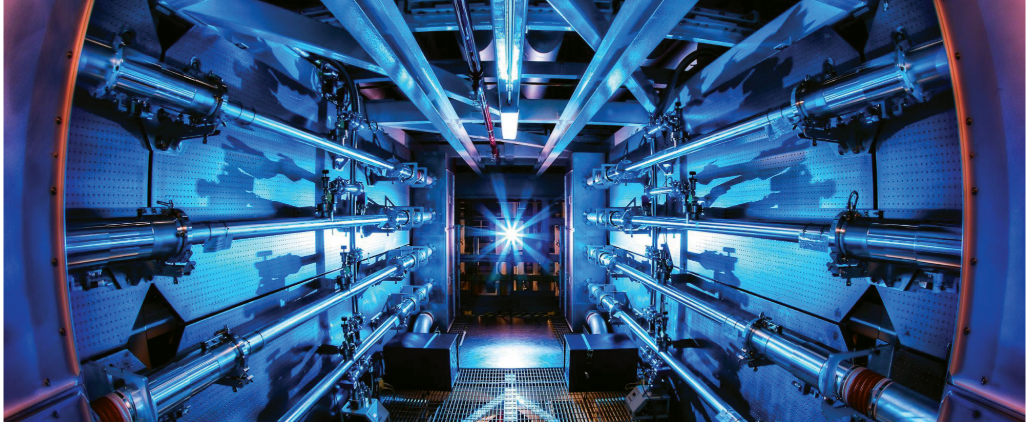
The identity of light elements in the core is a long-standing question. There is new relevance for this question as recent studies begin to appeal to specific light elements as an alternative source of energy for the geodynamo. An interesting possibility involves the exsolution of dissolved constituents in the core, such as magnesium. This work emphasizes the need to establish the composition of the core and to characterize the associated phase diagram. Progress will be made on many fronts. Advances in high pressure experiments should make experimental determination of phase diagrams more routine, particularly at high temperature. An improved understanding of the accretion process and the dynamics of giant impact offer a physical context for assessing proposed compositions.

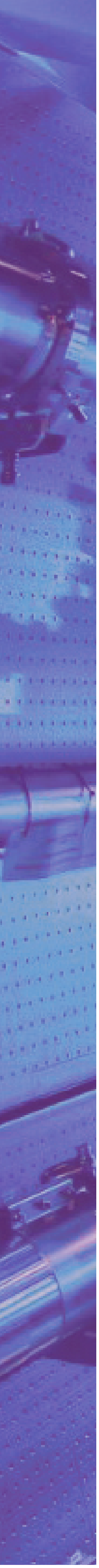
Understanding the origin of inner-core anisotropy is another important goal for research on the core. The existence of crystal fabric inside the inner core is most probably the outcome of processes that operate on geological timescales. By interpreting the structure revealed by modern seismic observations, we have the opportunity to gain insights into long-term processes. Better seismic observations and mineral physics information on the crystal structure, elastic properties and deformation mechanisms are critical for progress. We also require better geodynamic models that couple the evolution of the inner core with the dynamics of convection and magnetic-field generation in the outer core.

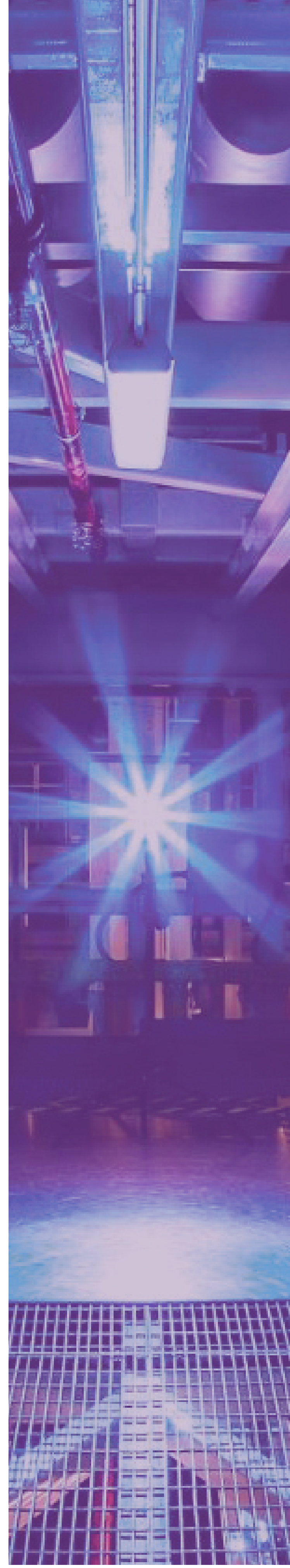
Surprises in our understanding of the geodynamo may be lurking behind the next major advance in approximating the parameter regime of the Earth's core. Even though the current models are remarkably successful, the field generation relies on large-scale, laminar flows. As more realistic values of fluid viscosity are achieved in numerical models, the flows are liable to become smaller in scale and more turbulent. Will the generation of magnetic field be unchanged by the emergence of turbulent flow, or will a new and entirely different style of field generation arise?

Efforts to interpret geomagnetic observations using numerical models rely heavily on having a correct description of the underlying dynamics. Evidence for stratification at the boundaries of the outer core has the potential to alter the underlying dynamics and change the way we interpret observations. Indeed, geomagnetic observations may contain the key signatures we need to quantify the extent of stratification (if any). Geodynamic models that integrate or couple models for the mantle and core may reveal the conditions under which chemical or thermal stratification is inevitable. Synergies between these efforts can aid our understanding of the planet as a dynamical system.

Significant challenges also remain in predicting secular change in the Earth's main magnetic field. Tools from modern weather forecasting may allow prediction, but evaluating those tools remains problematic due to the slow time scales of changes in the geomagnetic field. Forecasting tests using modern weather numerical prediction tools, coupled with modern geodynamo calculations, and laboratory experimental model data may be possible in cross-disciplinary projects involving researchers from several scientific communities.







Mineral Physics, Experiments and Calculations:

Progress in mineral physics research depends on the development of a wide-range of experimental techniques and computational approaches which enable researchers to simulate the extremely high pressure and temperature conditions found within the Earth's interior and then characterize the behavior of relevant materials in these extreme environments. This is an exciting time for both experiments and computer simulations. Experiments can now reach inner core pressures and temperatures and beyond (ramp compression experiments in 2014 at the National Ignition Facility (lasers.llnl.gov, see figure) compressed diamond to over 5 TPa which corresponds to pressures at the center of Saturn), can study more realistic (and complex) samples, and characterize materials properties using a large suite of in-situ and ex-situ techniques with unprecedented temporal and spatial resolution. Considerable progress in theory has also made enabling studies on larger and more complex unit cells containing many different atoms, amorphous (disordered) materials that require large and long simulations to reach equilibrium, strongly correlated materials such as iron-bearing phases, and the quantum behavior of hydrogen in hydrous phases. The experimental and theoretical sides are highly complementary, and the considerable volume of data being acquired from mineral physics (typically equilibrium states at individual P and T) must be organized into analytic and tabulated equation of state models that span the large phase space of Earth's origin and evolution. Experimental comparisons are critical for benchmarking theoretical approaches and must be provided in formats that can be broadly utilized by the geoscience community. In turn, theory can make predictions that provide guidance for experiments, can yield information that cannot be obtained by experiments, and can be extended to conditions unreachable by experiments. Linking this improved understanding of the behavior of Earth materials at the extreme conditions to seismic observations, geochemical constraints, and geodynamic models is crucial for addressing questions about planetary interiors. Mineral physics is constantly evolving and many advances in both experiment and theory have only recently been available. Realization of their potential for studies of the Earth's deep interior requires concerted and coordinated planning, research and development efforts much of which has been supported through community-based organizations like COMPRES: it facilitates the operation of beam lines, and the development of new technologies for high pressure research with the goal of enabling mineral physics researchers to conduct the next generation of high-pressure science on world-class equipment and facilities.

The preamplifiers of the National Ignition Facility are the first step in increasing the energy of laser beams as they make their way toward the target chamber. In 2012 NIF achieved a 500 terawatt shot—1,000 times more power than the United States uses at any instant in time.

V. DEEP EARTH TO SURFACE INTERACTIONS

There is a growing consensus that the surface conditions of Earth, including the climate, mass and composition of the atmosphere and oceans, are closely related to processes in Earth's deep interior through global and evolving long-term circulation of volatiles. Further, the balance of exchange of oxidized and reduced species have permitted formation of an oxidized surface whilst maintaining a reduced interior. Plate tectonics is the efficient mechanism to circulate materials between the surface and Earth's interior, but plate tectonics itself depends on material conditions in the mantle that are affected by surface-related materials, most notably volatiles. The nature of these feedbacks can be complicated and interdisciplinary studies among microscopic, mesoscopic and macroscopic scales are the key to the progress in this area.

Volatile circulation and its effect on surface and interior conditions.

Accomplishments

One of the most significant accomplishments in recent years has been an improved description of the role of deep earth volatile cycles, bringing with it an understanding of how hydrogen and carbon fluxes into and out of the mantle affect both interior and surface processes.

Much progress has been made on understanding the fluxes of these key actors at ridges and subduction zones. Improved estimates of H_2O and CO_2 fluxes from ridges come chiefly from geochemical studies of volatile and trace element concentrations in melt inclusions. A more limited number of studies show that oceanic islands sampling deeper mantle reservoirs are more volatile-rich, providing clues to the volatile concentrations of less accessible mantle domains. Oceanic islands may constitute fluxes of volatiles to the surface that rival those from ridges.

Petrologic constraints on potential hosts of H_2O during subduction in the upper mantle and transition zone are now reasonably well-characterized. There are also improved constraints on the degree to which subducting oceanic plate is hydrated with evidence of deep (~20 km or more) H_2O penetration caused by cracking due to thermal stress and/or to bending stress. If such deep hydration is global, it could increase the ingassing rate of water (hydrogen) by more than an order of magnitude. In the last 10 years, evidence has mounted that much of the carbon initially contained in sediments and altered oceanic crust is delivered to the deep mantle, but in fact recent work has shown that there are many intricacies to understanding the fluxes of carbon from subduction zones to island arcs and beyond, including the surrounding diffuse degassing through metamorphic belts (Fig. 12). Improved understanding of the fundamental character of C-H-O fluids at high pressure and temperature indicate much more complex speciation

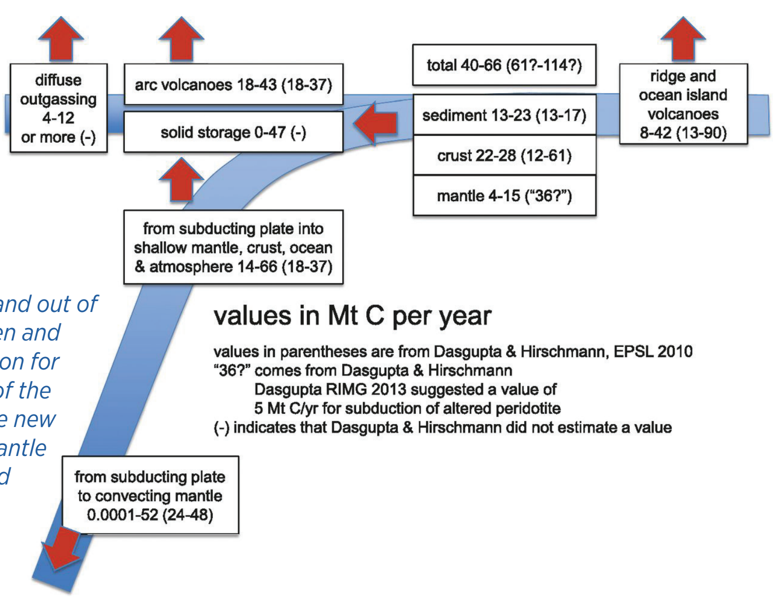


Figure 12. Inventories of C fluxes into and out of the mantle have been refined (Kelemen and Manning, 2015), with a new appreciation for the possible magnitude of fluxes out of the mantle above subduction zones. These new estimates suggest that the modern mantle C ingassing and outgassing rates could be approximately balanced, but leave open the possibility that ingassing exceeds outgassing substantially.

than was previously appreciated. Also, the retention or extraction of C from subducting slabs is known to be sensitive to the dynamics of fluid and melt flow through the architecture of subducted mantle, crust, and sediments. The release of volatiles from slabs subducted into the transition zone is implicated in a complex array of chemical and dynamic processes, including the origin of ultra-deep diamonds.

The fluxes of volatiles between the surface and the interior are both governed by and an influence on plate tectonics and simple geodynamic models have explored this coupling. Over long time scales, the depth of the oceans, and hence, the fraction of surface land versus water is controlled by the balance of H_2O ingassing to and outgassing from the mantle. A number of important elements of this system have been recognized, including the role of water on the strength of the lithosphere, the role of lithospheric bending outboard of subduction in introducing water into subducting lithosphere, and the influence of H_2O on the rheology of convecting mantle. Studies of the effect of volatiles on melting have improved understanding of the possible distribution of volatile-rich melt beneath ridges. Improved seismic and electromagnetic (EM) imaging seem consistent with considerable volatile-rich melt formation beneath ridges and possibly persisting beneath older lithosphere, though some of these observations can also be interpreted as owing to the influence of hydrogen in minerals.

The supply of gas species from the mantle, most notably CO_2, but also potentially including reduced species of C and H (as well as S, N, Cl and F), influence climate on several time scales, including emergence of snowball Earth conditions in the Proterozoic, during periods of high prevailing surface temperatures, such as the Cretaceous greenhouse and, through deglaciation-enhanced magmatism during glacial terminations in the Pleistocene. It has also been suggested that mantle volatiles play important roles in environmental crises associated with large igneous provinces.

Future Directions

We need better constraints on fluxes of volatiles from ridges. For example, recent estimates of C fluxes at ridges vary by more than an order of magnitude. Translation between observed fluxes, determined geochemically, and volatile concentrations in the sub-ridge mantle require detailed geophysical constraints, as it remains unclear what fraction of volatile-rich melts formed during the deepest portions of divergence-induced corner flow are channeled to the ridges or instead are trapped in overlying lithosphere. Distinguishing the influence of melt from that of hydrogen in minerals remains a major challenge. Improved seismic and MT resolutions are needed to distinguish and map the locus of deep melt and contrasts in H concentration.

Estimating volatile fluxes from oceanic islands has been hampered by the tendency of sub-areal volcanic products to degas during eruption. In particular, constraints remain sparse for the different enriched components identified from intraplate basalt sources (HIMU, EM, FOZO, etc.). These need to be integrated with geophysical constraints on mantle buoyancy, melting, and flow, as well as large-scale models of volatile circulation in the mantle through geologic time.

Significant problems in volatile ingassing relate to the ultimate fate of subducted volatiles. The downward continuation of H_2O-bearing transport during subduction depends in large part on the stability of a family of dense hydrous magnesian phases (DHMS), for which the spectrum of possible structures and their respective stabilities is only now beginning to be clarified. Significant questions remain regarding the fate of subducting carbon: H-C-O fluid equations of state need to be further developed; the possible interactions between C-rich melts and redox melting and freezing in the transition zone and deeper need to be clarified; and multiple possible phases of carbon, including diverse carbonate structures as well as reduced carbon (diamond/carbide/alloy) phases, could be principal hosts of deeply subducted carbon.

We still don't know well the influences between volatile storage and fluxes and geodynamical vigor of Earth's plates or deeper mantle, in part because the relationship is dependent on volatiles' influence on physical and chemical properties, some of which are not well constrained, particularly in the deeper mantle. Importantly, we don't understand well how the tuning between tectonics and volatile cycles originated: Does the initiation and regulation of modern plate tectonics require a particular range of volatile inventories in the interior and the surface (and if so, how did these arise)? Or, conversely, does plate tectonics naturally produce a particular distribution that is then self-regulating? And how are these inventories and fluxes linked to other surface processes?

Comprehensive geodynamic models for feedbacks between tectonics and climate are needed that couple mantle storage, upwelling (as in plumes) and outgassing to processes at time-scales ranging from 10^8-10^9 years, influencing continental freeboard, to 10^4-10^6 years, associated with the emplacement of large igneous provinces, down to 10^3-10^5 years, relating to the coupling between magmatism and glacial cycles..

Volatiles in the mantle: storage, effects, and geophysical observations

Accomplishments

The presence of hydrogen and carbon in Earth's deep interior was documented long ago by geochemical studies of basalts, and high-pressure experiments established plausible mineralogic hosts for these major volatiles. However, the actual modes of storage have been given quantitative constraints more recently, through experiments that constrain solubilities, storage capacities, partitioning and melting. A key finding has been that for modest volatile concentrations, small amounts of volatile-rich melt may be produced at a number of horizons. The large H storage capacities of transition-zone minerals give way to assemblages with lower storage capacities in the upper and lower mantles, making the horizons above 410 km and below 660 km likely sites for hydrous melting. In contrast to H, which is stored chiefly in the principal minerals of the mantle, storage of C in silicates is very limited, and so C is stored chiefly in accessory phases. Considerable progress has been made regarding the possible C-rich phases (carbonate, graphite, diamond, carbide, alloy, metal-rich melts). When comparatively oxidized conditions prevail, the solidus of carbonated mantle lithologies is at sufficiently low temperature that carbonatite or carbonated silicate melt is stable. Therefore, small amounts of carbonated melt could be present through much of the upper mantle, terminating at a depth where conditions become sufficiently reduced to stabilize an Fe-rich phase (Fig. 13).

Geophysical documentation of the presence of H and C in minerals and/or H and C-rich melts in the mantle and interpretation of their geodynamical behavior and geochemical significance require constraints on the effects of volatiles on mantle minerals and melts. Experimental constraints on the densities of H and C-rich melts have partly clarified these relations, for example, showing that melt atop the 410 km discontinuity may be denser than surrounding mantle, but complex dynamics and geochemical transport are to be expected because the density of melt relative to the solids is delicately controlled by the partitioning of key elements (H, Fe, Ca) and the relative fractions of H and C contributing to the stability of the melt. Experimental determinations of the effect of volatiles on elastic seismic properties of volatile-rich mantle have also been made, and initial determinations are also now available for anelastic effects, which are strongly influenced by H concentrations, allowing evaluation of seismic attenuation that has been mapped down to the transition zone. Progress has been made on the effects of H on the conductivity of mantle minerals as well as on the conductivity of H_2O-rich and CO_2-rich melts.

Receiver function and other seismic conversions above 410 km affirm that melting does occur above 410 km in many locations. More recently, receiver function studies enabled by the superior coverage of USArray have shown that melting also

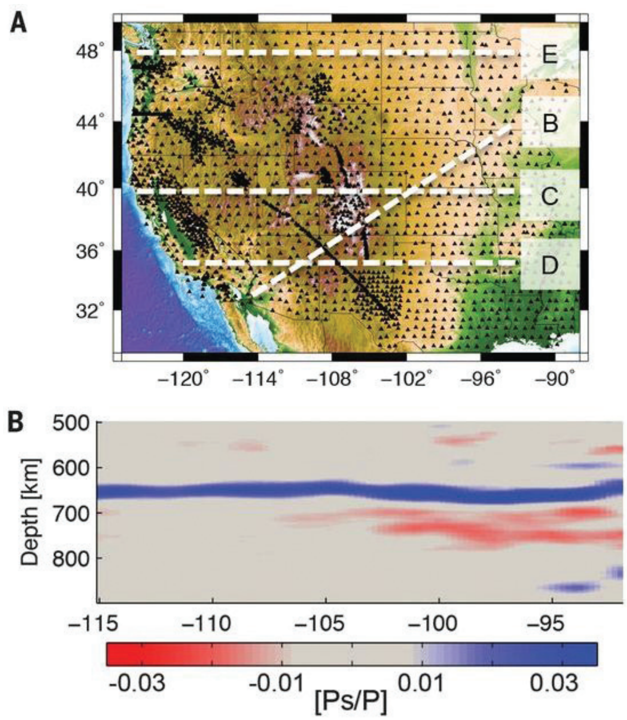
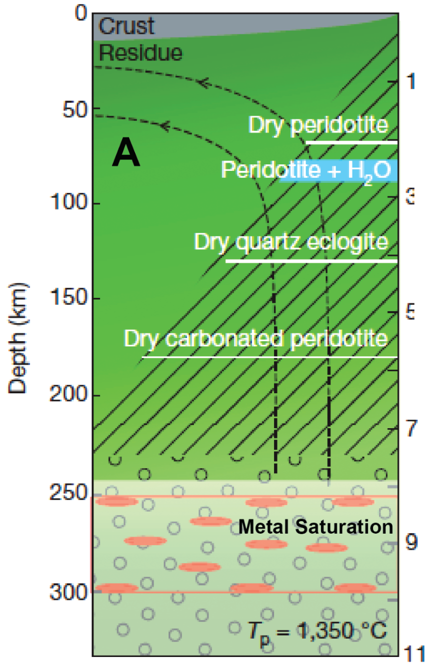


Figure 13. Cross section through western N. America showing P-S receiver function arrivals indicating a seismically low feature beneath the 660 km discontinuity that is interpreted to be owing to dehydration melting of mantle descending from the transition zone into the lower mantle (Schmandt et al. 2014)



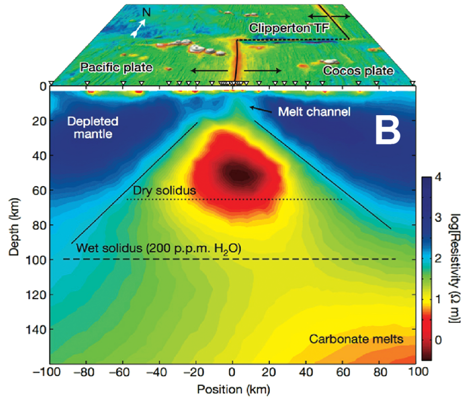


Figure 14. (A) Phase equilibria experiments suggest mantle upwelling beneath mid-ocean ridges generates small amounts of carbonatite or carbonated silicate melt at depths near 250 km, where conditions become sufficiently oxidized for C to be released from reduced refractory phases such as Fe-rich alloy (modified from Dasgupta et al. 2013). (B) Magnetotelluric maps of electrical conductivity beneath the East Pacific rise indicate high conductivity regions extending well below the depth of volatile-free melting, consistent with carbonate-rich melts in the deeper parts of the upper mantle (Key et al. 2013).

occurs beneath the 660 km discontinuity (Fig. 13). Documentation of C-rich melt in the oceanic upper mantle may include receiver function and S-wave precursor studies near the asthenosphere-lithosphere boundary, but in these cases alternative explanations related to subsolidus effects, including those related to the effect of H on mineral properties, are also viable. More persuasive are studies of high electrical conductivity, particularly at depth beneath mid-ocean ridges, which appear consistent with small amounts of CO_2-rich melt in the deep upper mantle (Fig. 14).

Future Directions

The question of H storage in the principal lower mantle minerals, bridgmanite, ferropericlase, and Ca-perovskite, remains unresolved and controversial, more than 10 years after the first (but conflicting) results were published. Alternatively, as in the case for subducted lithologies, there is the possibility of storage in dense hydrous magnesium silicates (DHMS). Some tantalizing evidence suggests that DHMS can be stable at the high temperatures of normal lower mantle, but more investigations are required. Carbon storage in the lower mantle is linked to redox state (discussed further below), and remains poorly constrained, though reduced Fe-rich phases (alloy, carbide, carbide melt, sulfide melt) seem most likely. Sulfur is unquestionably in a sulfide phase, but whether this is crystalline or molten depends in part on phase stoichiometry and the solidus-lowering potential of additional elements (e.g., C) and is poorly known. Finally, the storage of N and rare gases in the deep mantle is also of interest.

In tandem with questions of volatile storage (including partitioning and solubilities) in the deep mantle, experimental determinations of the effect of volatiles on the physical properties of solid phases, as well as on the stability and properties of melts and fluids are also needed to understand the fluxes of volatiles between the interior and the surface, as well as between different interior reservoirs.

Additional important questions relate to the mechanisms of volatile circulation and segregation in the mantle. It is now well established that diffusion (in solid minerals) is so inefficient that macroscopic materials transportation is needed to transport materials. Separation of materials involving liquids is essential. The nature of such processes depends on a number microscopic and mesoscopic materials properties (density, contact angle between liquids and solids) as well as viscosities of both solids and liquids. However, current understanding on the density contrast between liquids and co-existing minerals is highly limited. There is no data on the dihedral angles between melts and minerals in the transition zone and the lower mantle. Both micro- and meso-scopic materials properties and of the macroscopic physics of materials transport need to be studied through interdisciplinary efforts.

Documentation of the distribution and consequences of deep volatile storage also require further studies on seismic wave attenuation (and tidal dissipation). Combined studies of attenuation and electrical conductivity may enable constraints on the water content in Earth's mantle, but at this time, the resolution of attenuation in the deep mantle is still poor. Equally or more serious is that reliable experimental studies on attenuation have been limited to low pressures (P<0.2 GPa).

Finally, many of the links between geodynamics, volatile cycles, and surface fluxes are through rheology. Plastic flow laws incorporating the effects of H_2O±melt need to be extended to higher pressure, taking into account changes in slip mechanisms, H substitution, and ultimately phase transitions to allow modeling of flow in the transition zone and lower mantle.

Improved constraints on mantle redox variations with tectonic domain and mantle history

Accomplishments

The redox state of the mantle is known to affect its geochemical, petrological, and physical properties, but also reflects the compositional history of enrichment and depletion, particularly as it relates to the flux of oxidized and reduced materials associated with melting and recycling via subduction. Innovations in high-precision analysis of Fe^{3+}/Fe^{T} in fresh volcanic glasses has permitted documentation of correlations between the redox state of basalts and their geochemical history of enrichment. A global survey of mid-ocean ridge basalts (MORB) documents a negative correlation between geochemical indicators of a recycled component and the Fe^{3+}/Fe^{T} of basalt (Fig. 15). This either suggests that recycling of crust introduces reduced materials into the mantle, for example subduction of reduced carbonaceous sediments during the Archean, or that the process of enrichment eventually leads to reduction, perhaps owing to more extensive conversion of reduced carbon to carbonate during redox melting. Thus, mantle redox is coupled both to the processes of mantle differentiation and to cycling of volatiles through the deep Earth.

The oxygen fugacity of the mantle relative to standard buffers such as quartz-fayalite-magnetite (QFM) or iron-wüstite (IW) becomes more reduced with depth, owing to stabilization of Fe^{3+} in high pressure mantle minerals. Increased stability of Fe^{3+} relative to Fe^{2+} in minerals influences other key elements—for example highly fusible carbonate is stable in the shallow mantle, but more refractory C phases become stable at depth, and so the redox gradient controls the locus of C-rich melts in the mantle. Ultimately Fe^{3+} stabilization leads to disproportionation, with reduced Fe precipitated as an FeNi alloy phase and/or dissolved in sulfide or carbide. The stabilization of such

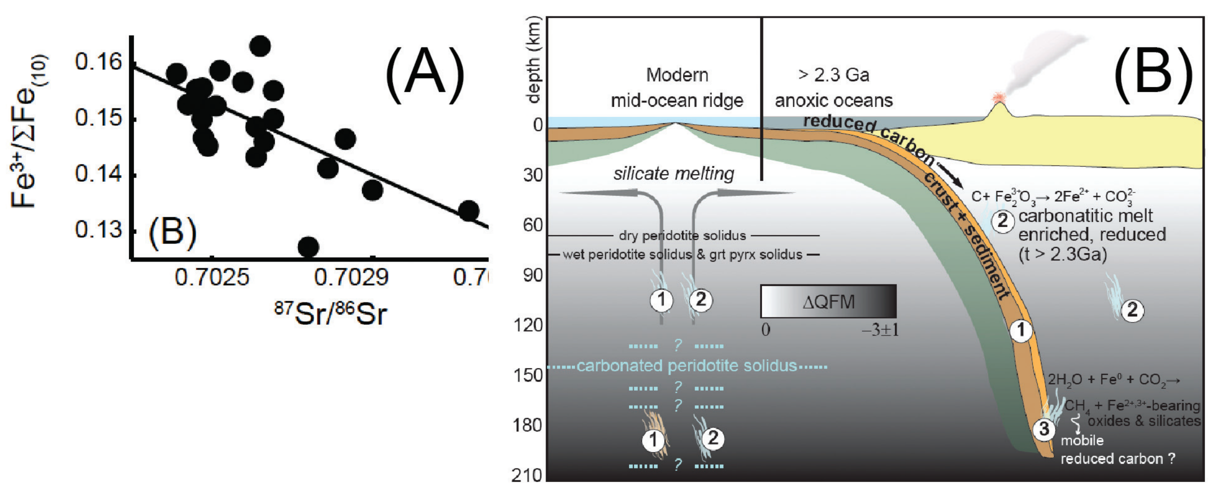


Figure 15. (A) Fe^{3+}/Fe^{T} of a global survey of MORB glasses, determined by XANES spectroscopy, correlate negatively with geochemical indicators of enrichment, such as $^{87}Sr/^{86}Sr$. (B) Possible scenarios to account for the relationship between geochemical reservoirs and mantle redox include either subduction of reduced materials from an early Earth, prior to the rise of oxygenated conditions on the surface or an initial enrichment in C in recycled materials, leading to greater reduction of Fe^{3+} to Fe^{2+} during upwelling beneath ridges, as C reduced at depth becomes oxidized to carbonate-rich melt, inducing the reaction $2Fe_2O_3 + C = 4FeO + CO_2$. Data and Figure are from Cottrell and Kelley (2013).

phases has potential effects on the geophysical and geochemical character of the mantle, particularly if the phase is molten and can affect transport properties and/or can feasibly migrate. The stability of Fe^{3+} in upper mantle, transition zone, and lower mantle phases is linked to crystal chemical effects, such as coupled substitution with Al^{3+} and, in the lower mantle, spin transitions. Finally, evidence from deeply subducted diamonds includes phase assemblages that suggest comparatively oxidized conditions in at least some domains of the lower mantle, chiefly associated with subduction. Interactions between oxidized and reduced domains may be responsible for important mass transfer, including deep melting, metasomatism, and diamond formation.

Future Directions

The stability of possible metal-rich phases, including Fe-Ni±C±S solid and liquid alloys requires investigation, as do the possible detection of such phases with geophysical methods, and exploration of the geodynamic behavior of mantle with small amounts of solid or liquid alloy-rich phases.

The history of mantle redox also presents important questions and challenges. The rock record shows scant evidence of secular changes of oxidation of average mantle through time, possibly suggesting that most subducted oxidized material is returned to the surface in island and continental arcs. Ultra-deep diamonds suggest that at least some oxidized material is injected into the deep mantle, but the fate of such deeply subducted carbon is not known. Finally, the mantle has been implicated in the rise of an oxygen rich atmosphere at 2.4 Ga either owing to a change in the character of mantle degassing or as a deep sink for complementary reduced material, possibly in the form of subducted organic carbon. Further documentation of the possible causes and effects of large-scale surface oxidation on the interactions between the surface and the mantle are needed.

Volatile elements in the Core?

Accomplishments

Experiments and ab initio calculations have explored the storage capacity of light elements (H, C, Si, O, and S) in the core and of the partitioning of these elements between the molten and solid Fe. The partition coefficient between the solid and molten Fe appears to be specific for each candidate element; wide variations have been documented in the pressure, temperature and redox conditions. There is also growing confidence in the influence of light elements on the sound speed in Fe. Combined with seismologically inferred densities and sound speeds in the outer and the inner core, these studies provide tighter constraints on the composition of the core and also form the basis for understanding the evolution of the core through the growth of the inner core. The abundance of light elements in the outer core estimated from these studies show that the geophysically inferred properties of the outer core can be explained by some combination of light elements. In some instances, the absolute concentrations needed to account for geophysical observations are less than the solubility limits at current CMB conditions. This important inference indicates that the core could be a sink for some elements.

Future Directions

Owing to the many unknowns compared to available constraints, there remain major challenges to determining the combination of light elements in the core from laboratory and geophysical observations. An important goal is to identify new parameters or observations that constrain the nature of light elements in the core. Among the light elements, recent investigations have focused less on role of H in the core, in part owing to significant experimental challenges, but H may have an important effect on key physical properties such as thermal conductivity. Experimental and theoretical studies are needed to understand the effect of H on the energetics of the geodynamo, but also to quantify the core's role in global water circulation. Because the core is arguably the largest terrestrial volatile reservoir, the nature of core-mantle exchange of all volatiles needs further experimental, geophysical, geochemical and theoretical studies.

VI. INFRASTRUCTURE

The study of the Earth's deep interior requires observations and modeling capabilities from a broad range of disciplines. Many of these disciplines already have vital facilities and data resources that are funded by NSF, the Department of Energy (DOE) and others. For example, NASA observations from both satellites and aircraft are a critical resource. Here we list some of these facilities and how they contribute to deep Earth research.

SAGE/GAGE

NSF currently supports two high-quality community-governed geophysical facilities: SAGE (Seismological Facilities for the Advancement of Geosciences and EarthScope), and GAGE (Geodesy Advancing Geosciences and EarthScope). Both of these facilities support the enormously successful **EarthScope** program but actually do much more.

SAGE is currently managed by **IRIS** (Incorporated Research Institutions for Seismology)
IRIS has been central to seismological research in the US for over 30 years. It has supported the generation of global seismic datasets through its GSN and PASSCAL programs and made these datasets easily available through its Data Management Center. It is these datasets that have allowed the tomographic imaging of the Earth's interior and have driven much of the work described in this report.

IRIS also operated many parts of the enormously successful EarthScope program including the Transportable Array, which has led to unprecedented seismic images of the mantle beneath the US. These are complemented by resistivity images deduced from another component of Earthscope, the magnetotelluric survey of the US. Combining EM and seismic data in geophysical inversions is now a leading research area.

Many of the most intriguing geoscience problems occur at plate margins and SAGE has successfully integrated onshore/offshore observational capabilities in both seismological and electromagnetic areas to allow comprehensive experiments to be undertaken. In particular, the OBSIP program has allowed the offshore extension of experiments designed to look at some of the nation's most potentially dangerous seismic zones so facilitating a complete imaging of the subduction zone system. The importance of this type of tectonic setting led to the formation of **GeoPRISMS,** an NSF-supported community effort that studies the origin and evolution of continental margins, demonstrating just how critical the SAGE facility is for a large cross section of deep Earth research.

GAGE is currently managed by UNAVCO and has focused on crustal deformation and so far has had less impact on deep Earth research. However, recent geodetic instrumentation of polar regions has led to new research in glacial isostatic adjustment using combinations of seismic and geodetic data. This is also a new leading research area.

SAGE and GAGE are currently being re-competed—it is very important for the CSEDI community that both facilities maintain their current capabilities and, if at all possible, extend them in new directions. In terms of deep Earth research, a major limitation in the quality of tomographic imaging has always been the geographical distribution of receivers. New developments have allowed the reliable operation of seismic stations in extreme environments, an example being Antarctica, which has been poorly instrumented until recently. Of course, the major impediment to global coverage is the difficulty and expense of operating stations on the ocean floor. New technologies, such as wavegliders, hold out the hope for affordable sea-floor operation in the near future. These are outlined in a detailed report on **Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences,** (2015) on plans for SAGE/GAGE facilities.

Mineral physics is central to CSEDI research in that it provides the means of testing seismological and EM models with possible compositions and phase assemblages, but also provides crucial experimental constraints on rheological and transport properties which are essential to geodynamical calculations. Mineral physics has also embraced computational approaches to predicting physical properties and transport properties and so has needs for high performance computation (HPC). We shall return to this point later as many areas of CSEDI research now need HPC resources.

COMPRES

The mineral physics community has done more than most to leverage existing facilities. COMPRES, an NSF-supported community governed group, supports a variety of facilities serving the high pressure mineral physics community, including several synchrotron beamline stations in addition to other user support projects. Indeed, COMPRES makes it possible for junior faculty at small institutions to do major, cutting-edge research in deep Earth science and gives them access to major infrastructure facilities.

COMPRES Synchrotron Beamline Facilities include:

- Advanced Light Source Beamline 12.2.2—Diamond anvil cell; Single crystal/powder X-ray diffraction
- Advanced Photon Source 13-BM-C—Diamond anvil cell; Single-crystal/powder X-ray diffraction
- Advanced Photon Source 6-BM-B—Large volume press; white X-ray diffraction
- National Synchrotron Light Source II FIS—Diamond anvil cell; Infrared spectroscopy [available 2018]
- National Synchrotron Light Source II XPD—Large volume press; mono X-ray diffraction and radiography

These facilities are dominantly supported by DoE.

Other COMPRES Project Facilities include:

- Advanced Photon Source Sector 3—Support for inelastic X-ray scattering in the diamond anvil cell
- Advanced Photon Source Sector 13—Gas loading for diamond anvil cell sample preparation
- Arizona State University—Multianvil press assembly development and fabrication
- COMPTECH project—Support for development of new high pressure applications at additional sectors of the Advanced Photon Source

Looking to the future, the development of next generation X-ray sources like free electron lasers promise measurements with unprecedented temporal resolution. As the world's first hard X-ray laser, Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory, the LCLS creates ultrafast and ultrabright x-ray pulses that can see details down to the size of atoms and processes that occur in less than a trillionth of a second. At these unprecedented speeds and scales, the LCLS can address dynamic questions in many diverse fields include Earth and planetary sciences. Large laser facilities like the National Ignition Facility (NIF) may also provide opportunities for laser-shock compression experiments at the extremely high P-T existing in the centers of giant planets and stars.

Computational Infrastructure for Geodynamics

As noted above, mineral physics, seismology and geodynamics all require access to high performance computing. But access to high-quality community codes is just as important and this is where CIG (Computational Infrastructure in Geosciences)—another NSF-supported, community governed group plays a critical role.

Computational modeling has emerged as a fundamental tool for answering geodynamics questions. The growing reliance on computational modeling has produced a corresponding need for computational infrastructure. The Computational Infrastructure for Geodynamics advances deep-earth science and related scientific research through development and dissemination of scientific software for geophysics and related fields. CIG hosts more than 30 software packages developed with CIG support or donated by the community, for modeling related to the geodynamo, seismology, mantle dynamics, long and short term tectonics, and related science. CIG provides training, support for best practices for software development, and assistance with access to national computational resources on XSEDE and other platforms.

CIG has fundamentally changed the way that research is done. Graduate students are no longer required to develop their own computational models to investigate problems of interest. Instead, researchers can start with well tested and well documented codes to initiate their studies. Training and hands-on experience ensures that researchers do not simply use CIG code as a black box. More importantly, CIG builds on the successes and advances of individual researchers by providing a means of incorporating valuable new capabilities into new versions of the codes. CIG has also been successful in engaging the broader Computational Sciences community to exploit the latest developments in other fields.

Of course, the ability to take advantage of these codes implies access to HPC resources.

High Performance Computing

The increasing importance of computation in seismology, mineral physics, mantle dynamics, and geodynamo simulations requires access to high-performance computing from the desktop to leadership class computing. Resources currently being used for deep earth research include computer clusters at individual institutions, NSF's XSEDE supercomputers and associated resources, the NCSA Blue Waters, and DOE's INCITE program for Leadership-class scientific computing. Many institutions find it challenging to build, operate, and sustain the mid-scale computing required for deep-earth modeling; similarly the demand on national resources is increasing with larger, higher-resolution models.

Geochemistry

Necessary geochemical infrastructure to address the challenges associated with deep earth research include a combination of dedicated PI-supervised laboratories and national user facilities.

PI-run infrastructure include both capabilities for analysis of natural rocks and minerals and for experimental determinations of chemical and physical properties of rocks and minerals across a range of conditions. The type of work done by PIs with CSEDI related research goals has included high-precision isotope ratio mass spectrometry, including state-of-the-art thermal or plasma ionization mass spectrometry (TIMS and MC-ICP-MS), secondary ionization mass spectrometry (SIMS), gas source mass spectrometry, through to 'workhorse' type instruments where chemical abundance information is sought, such as inductively coupled plasma mass spectrometry (ICP-MS), laser-ablation methods and other microbeam or imaging techniques,including electron microprobe analyzers. Experimental facilities include both laboratories focused on physical properties (equations of state, conductivity, rheology, density, elastic and anelastic behavior, etc.) of materials as well as chemical properties including (but not limited to) melting relations, diffusivities, and element partitioning. These types of PI facility, and existing or next-generation infrastructure will remain a crucial part of deep earth research goals.

Principal national platforms for geochemical research are synchrotron-based facilities that provide in situ spectroscopic interrogation of high pressure, high temperature experiments, including both diamond anvil and solid media apparatuses for both near-hydrostatic and dynamic (deformation) conditions and that allow in situ sample interrogation via x -ray diffraction and scattering, Brillouin spectroscopy, and synchrotron Mossbauer spectroscopy. Beamlines also provide crucial analytical facilities for x-ray spectroscopy of natural and experimental samples.

National user facilities based at universities include SIMS laboratories for high spatial resolution geochemical analysis of natural and experimental materials relevant to understanding Earth's interior.

Further advances in the geochemical field are likely to include improved numerical models and gas-gun technologies to investigate EOS in silicate melts and iron alloys as well as advances in mass spectrometry and advanced measurements.

EarthCube and other Data Initiatives

Interdisciplinary work relies heavily on open access to community data and models that can be assimilated into different fields. EarthCube (earthcube.org) was launched in mid-2011 as a collaborative partnership between National Science Foundation's (NSF) Directorate for Geosciences (GEO) and the Division of Advanced Cyberinfrastructure (ACI), with the goal of creating a more sustainable future through better understanding of Earth as a complex and changing planet. EarthCube has yet to fully define the goals that will allow it to mature to its full potential, but they are wide ranging and interdisciplinary.

Data retention and availability has been facilitated by a number of websites, including the Interdisciplinary Earth Data Alliance (IEDA) which is a community-based data facility funded by the US National Science Foundation (NSF) to support, sustain, and advance the geosciences by providing data services for observational solid earth data from the Ocean, Earth, and Polar Sciences. A number of other geochemical and 'big data' databases, including PetDB, SedDB, GEOROC, NAVDAT, USGS, and GANSEKI can be accessed through this portal (www.iedadata.org). Data on Geological and Environmental Reference Materials is supported by the GEOREM database as well as Earthref.org (earthref.org). The paleomagnetic community has made significant efforts through MagIC (Magnetic Information Consortium, /EarthRef.org/MAGIC to archive the most basic data from numerous studies in rock and paleomagnetism. It is now necessary to augment the success of these multiple individual endeavors by supporting interoperable databases and software. For example, a key functionality in future will be for dynamic reconstruction software like GPlates (www.gplates.org) to provide state of the art information to databases like MagIC and vice versa. The EarthCube initiative should ultimately greatly facilitate such efforts and other forms of data discovery and integration.

VII. THE FUTURE OF CSEDI: CONCLUDING REMARKS

Although the CSEDI program is now over 20 years old, the motivation for having such a program remains the same: all of the fundamental problems in understanding the origin of the Earth and the evolution of heat and mass transport over geological time are fundamentally interdisciplinary. Here, we are usually speaking of disciplines within the Earth Sciences: seismology, mineral physics, geodynamics, geomagnetism, petrology, and geochemistry. CSEDI leverages the enormous investments in infrastructure that underpins these disciplines even though this infrastructure often primarily serves other communities (e.g., geoneutrinos, properties of materials at extreme conditions—see sidebars above). Because of this leverage, the relatively small CSEDI program has been able to have large impact, both on CSEDI goals and extending beyond earth sciences.

In the past, the size of the program has meant that a few relatively small collaborative projects can be funded at any one time. These have included multiple PI's from several institutions or even from a single institution. The program has also been flexible enough to fund single discipline studies if the focus is on a product of use to many (e.g., reference Earth models or important databases). The question remains whether or not the program should be allowed to grow.

Ten years ago, there was a recommendation that the program should at least double in size to a still-modest $5M per year. We believe that this should be a minimum level of funding for CSEDI, particularly if the CIDER project (see sidebar above) or other large-scale efforts are to be accommodated within the CSEDI program.

Multi-institutional, multi-disciplinary proposals tend to be expensive. A modest $150K annual budget for a single PI rapidly becomes a $0.5M/yr budget for a multi-institutional proposal and this budget will rise even faster if fieldwork or lab work is required. Given the current budget constraints, it is very difficult for CSEDI to consider proposals at the $1M/yr level so such projects have simply not applied to the program. Even at $5M/yr, the program will still be able to fund relatively few projects, and there are no clear alternative programs within NSF or elsewhere that can fund this kind of study.

The CIDER project has been an enormously successful program in training and enabling young scientists to work together in an interdisciplinary setting. This has led to a sea-change in the way many of our young researchers think about our science and has facilitated many interdisciplinary projects. Clearly, the CIDER program should continue. In the past few years, this program has been funded by the FESD program at NSF and was able to grow and expand its reach. Unfortunately, the FESD program has ended and a new home must be found for the next phase of CIDER. The CSEDI program is a natural place but only if the CSEDI budget is expanded.

In summary, the CSEDI program currently fills an important niche by funding a few relatively small interdisciplinary collaborations a year. The sentiment from within the community is that many more and worthwhile projects would be submitted with a modest increase in funding. Expanded funds could also allow a few larger projects with potentially much higher impact to be funded. This could facilitate the continuation of the important CIDER program. We believe that this would allow an already successful program to have a very bright future.

Acronyms

ACI *Advanced CyberInfrastructure*

CSEDI *Cooperative studies of Earth's Deep Interior*

CIDER *Cooperative Institute for Dynamic Earth research*

CIG *Computational Infrastructure for Geodynamics*

CISE *Computer & Information Science and Engineering (NSF)*

COMPRES *Consortium for Material Properties Research in Earth Sciences*

DOE *Department of Energy*

EAR *Division of Earth Sciences (NSF)*

FESD *Frontiers of Earth System Dynamics*

GAGE *Geodesy Advancing Geosciences and EarthScope*

GANSEKI *Geochemistry and Archives of ocean floor rocks on Networks for Solid Earth Knowledge Integration*

GEO *NSF GEO Directorate*

GeoPrisms *Geodynamic Processes at Rifting and Subducting Margins*

GEOREM *Geological and Environmental Reference Materials*

GEOROC *Geochemistry of Rocks of the Oceans and Continents*

IEDA *Interdisciplinary Earth Data Alliance*

IGSN *International Geo Sample Number*

INCITE *Innovative and Novel Computational Impact on Theory and Experiment (US DOE, program)*

IRIS *Incorporated Research Institutions for Seismology*

KITP *Kavli Institute for Theoretical Physics*

LCLS *Linac Coherent Light Source*

MagIC *Magnetics Information Consortium*

MT *Magnetotellurics*

NASA *National Aeronautics and Space Administration*

NAVDAT *North American Volcanic and Intrusive Rock Database*

NCSA *National Center for SuperComputing Applications*

NIF *National Ignition Facility*

NSF *National Science Foundation*

PetDB *the Petrological DataBase*

SAGE *Seismological Facilities for the Advancement of Geosciences and EarthScope*

SedDB *Sediment Database*

SLAC *Stanford Linear Accelerator Center*

STEM *Science, Technology, Engineering and Mathematics*

UNAVCO *University NAVSTAR Consortium*

USGS *United States Geological Survey*

XSEDE *Extreme Science and Engineering Discovery Environment*

Reference Materials and Acknowledgments

Funding for the 2015 workshop and this report was provided by NSF under Grant Number EAR 1406437. In addition to input from CSEDI researchers, our discussions were informed by numerous national reports and community studies listed below, together with credits for the images used in this report. We are most grateful to Jennifer Matthews for her help in producing this report.

Cooperative Studies of the Earth's Deep Interior: Developments, Discoveries, Future. 2004, http://csedi.org/CSEDI_plan_2004.pdf

CSEDI Science Plan: A Science Plan for Cooperative Studies of the Earth's Deep Interior. 1993, http://csedi.org.edu/csedi_1993.pdf

Dynamic Earth: GEO Priorities and Frontiers 2015–2020 https://www.nsf.gov/geo/acgeo/geovision/nsf_ac-geo_dynamic-earth-2015-2020.pdf

Earth Science Literacy Principles: The Big Ideas and Supporting Concepts of Earth Science http://www.earthscienceliteracy.org/es_literacy_6may10_.pdf

Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences (2015) http://www.iris.edu/hq/publications/meeting_materials

Geovision Report. 2009, NSF Advisory Committee for the Geosciences, https://www.nsf.gov/geo/acgeo/geovision/nsf_ac-geo_vision_10_2009.pdf

It's About Time: Opportunities and Challenges for U.S. Geochronology. 2015, T.M. Harrison, S.L. Baldwin, M. Caffee, G.E. Gehrels, B. Schoene, D.I. Shuster, and B.S. Singer, http://www.princeton.edu/geosciences/people/schoene/pdf/2014_geochronologyreport_FINAL.pdf

Living on a Restless Planet. 2002, NASA Solid Earth Science Working Group Report, http://solidearth.jpl.nasa.gov/PDF/SESWG_final_combined.pdf

Review of NASA's Solid-Earth Science Strategy (2004), http://www.nap.edu/read/11084

New Research Opportunities in the Earth Sciences. 2012, http://www.nap.edu/read/13236/

Origin and Evolution of Earth: Research Questions for a Changing Planet. 2008, http://www.nap.edu/read/12161/

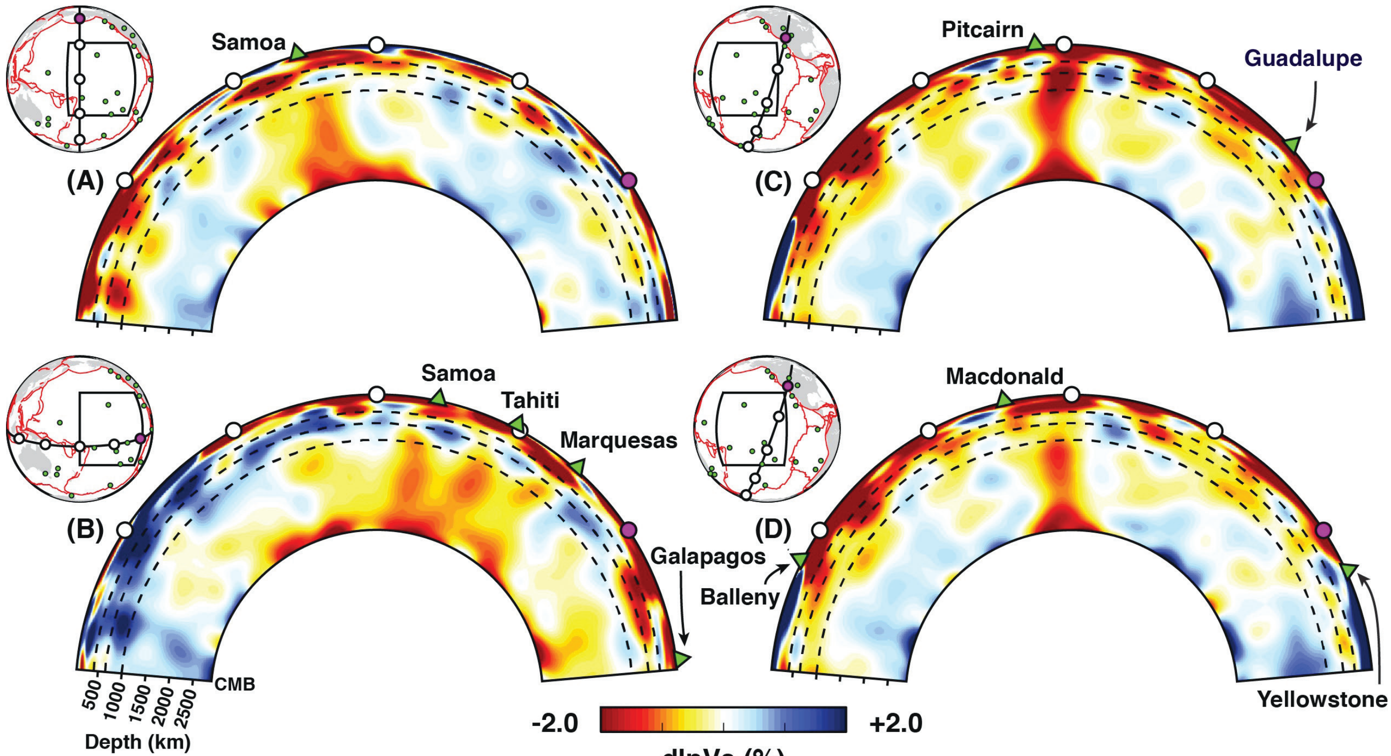
Status of the Geoscience Workforce. 2014, Carolyn Wilson, http://www.americangeosciences.org/workforce/reports

Strategic Frameworks for Education & Diversity, Facilities, International Activities, and Data & Informatics in the Geosciences, 2012, http://www.nsf.gov/geo/acgeo/geovision/geo_strategic_plans_2012.pdf

Striving to Diversify the Geosciences Workforce. 2010,http://onlinelibrary.wiley.com/doi/10.1029/2010EO330001/epdf

Understanding the Building Blocks of the Planet: The Materials Science of Earth Processes http://www.compres.us/index.php?option=com_docman&task=doc_download&gid=256&Itemid=92

List of Figures



Broad plumes at the base of the mantle (modified from French and Romanowicz, 2015): Whole-mantle depth cross-sections of relative shear-velocity variations in model SEMUCB-WM1, in the vicinity of several major hotspots.

Page 33

Fig 13. Schmandt, B., S.D. Jacobsen, T.W. Becker, Z. Liu, K.G. Dueker (2014) Dehydration melting at the top of the lower mantle, *Science,* 344 (6189) 1265-1268, doi 10.1126/science.1253358

Page 34

Fig 14a. A. Dasgupta, R. Mallik, A., Tsuno, K. Withers, A.C. Hirth, G. Hirschmann, M.M. (2013) Carbon dioxide-rich silicate melt in Earth's upper mantle. *Nature,* 493 211-215, doi:10.1038/nature11731, Figure 4a.

Fig 14b. Key, K., S. Constable, L. Liu, and A. Pommier (2013) Electrical image of passive mantle upwelling beneath the northern East Pacific Rise, *Nature,* 495, 499-502, doi:10.1038/nature11932, Figure 2.

Page 35

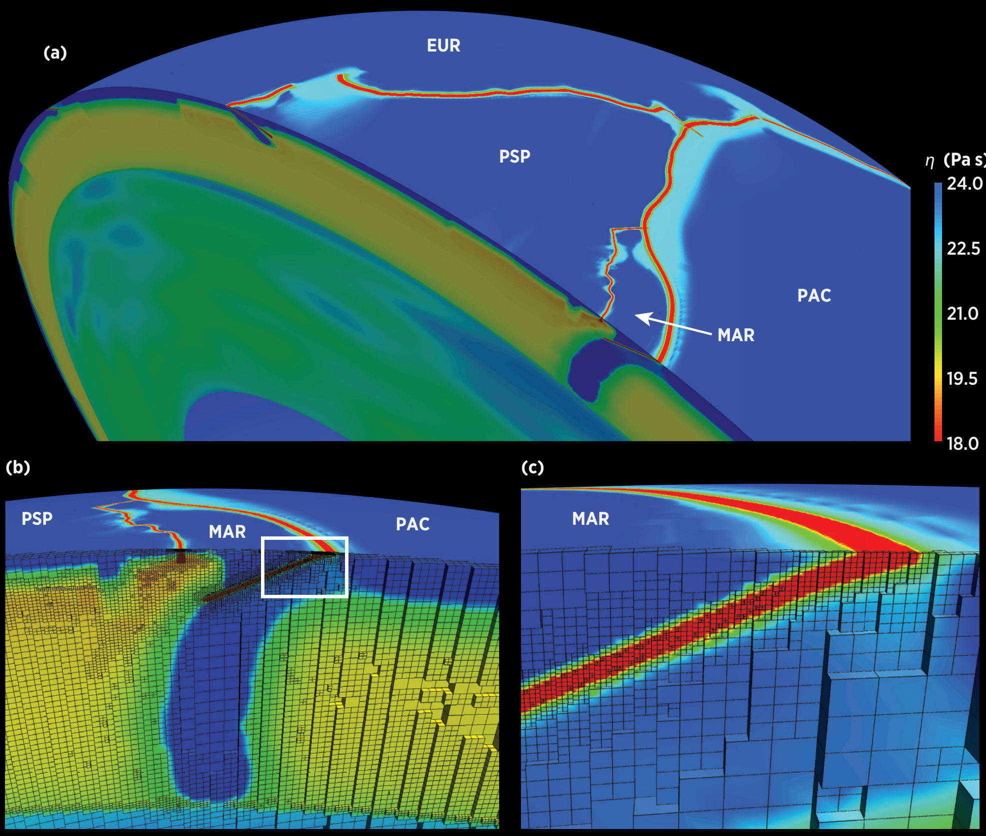
Fig 15. Cottrell E., Kelley K.A. "Redox Heterogeneity in Mid-Ocean Ridge Basalts as a Function of Mantle Source." *Science,* 340, pp. 1314-1317. doi:10.1126/science.1233299. 2013. (A) Data re-plotted from Figure 1B (B) Figure S6.

Inside back cover

Adapted from: French, S. W., Romanowicz, B. R. (2015), Broad plumes rooted at the base of the Earth's mantle beneath major hotspots, *Nature,* 525, 95-99, doi: 10.1038/nature14876

Back Cover

Alisic, L., M. Gurnis, G. Stadler, C. Burstedde, O. Ghattas, (2012) Multi-scale dynamics and rheology of mantle flow with plates, *J. Geophys. Res.,* 117, B10 doi: 10.1029/2012JB009234



*(a) Cutout showing viscosity in a global mantle flow model through the Marianas and Philippines. (b) Zoom-in on viscosity of the Marianas subduction zone, showing the mesh. (c) Further zoom-in on the hinge of the Marianas slab, as denoted by the white box in (b). Plate labels are: **EUR:** Eurasia; **MAR:** Marianas; **PAC:** Pacific; **PSP:** Philippine Sea (from Alisic et al, 2012).*