Grand Challenges in Geodynamics

Outstanding geodynamics problems and emerging research opportunities for the Earth Sciences

March 1, 2010

Preface

This report was conceived at the Opportunities and Challenges in Computational Geophysics, a National Science Foundation supported workshop held at Caltech in March 2009, and initiated at the request of the U.S. geodynamics community. The purpose of this report is to describe the major scientific challenges in geodynamics, discuss some new and emerging research opportunities these challenges present, and suggest some promising approaches to their solution. In addition, we seek to convey the current state of our science including recent progress, and where we think geodynamics may be headed in the future. Lastly, we suggest some educational and training goals and describe some key technical facilities that will be needed to meet these challenges.

We intend this report be accessible to, and hopefully compelling for, a broad range of interested parties, including administrators of scientific research institutions and science funding programs, graduate students, beginning researchers, and our colleagues in allied disciplines who have an interest in learning more about the current state and future prospects of geodynamics.

The writing group listed below represents the broad scope of expertise as well as the diversity that exemplify the geodynamics research community in the U.S. today. In constructing this report, our writing group drew upon a great many discussions with our colleagues, as well as their research publications and presentations. Their contributions, in the form of new ideas, research problem descriptions, and graphical display materials, have been instrumental to this document.

One problem we had to contend with from the outset was selecting a tractably small number of Grand Challenge questions to report on. We consulted with members of the geodynamics community at a number of meetings, workshop and conference venues, and after debating the relative merits of a set nearly twice the final size, we arrived at the ten Challenges that make up this report. Not all of the final ten are equally amenable to progress now, and indeed some will not likely be resolved in the near future. Nevertheless, they all have outstanding merit, and in the end, our committee found it relatively easy to come to a consensus.

Cover Illustration: Earth's Interior. Courtesy: Calvin J. Hamilton, http://www.solarviews.com

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Executive Summary

Geodynamics occupies a unique position in the solid Earth Sciences. First and foremost, it is primarily concerned with the dynamical processes that affect the Earth, especially within its interior but also at its surface. Geodynamics is also applied to the interiors and surfaces of other terrestrial planets and satellites, within our solar system and beyond. As a scientific discipline, geodynamics is distinguished from other Earth Science disciplines in that it usually starts from fundamental physical principles to interpret and predict Earth's behavior, rather than working backwards from observations. Second, geodynamics explicitly treats Earth's complex material properties, in addition to its dynamics. Indeed, many of the important geodynamical processes described in this report owe their existence to the interplay between complex material behavior, dynamics, and Earth structure. Lastly, geodynamics relies very heavily on field data, in addition to laboratory data. Often this field data is acquired remotely, from satellite, ship-board, seismic, or astronomical measurements for examples, or over long periods of time, as with GPS and other geodetic measurements.

This report starts from the recognition that the major paradigms shaping the solid Earth Sciences over the past decades are essentially geodynamics concepts. Perhaps the best known of these are plate tectonics and the associated movement of the continents. These have stood the test of time, have been confirmed by repeated measurements, and are now acknowledged as the basic phenomena governing the long-term evolution of the Earth's crust. A second fundamental paradigm is mantle convection. Convection in the mostly solid silicate-oxide mantle is the basic engine for plate tectonics and is the most important process controlling the long-term evolution of our planet's interior, including its temperature and composition. Understanding the diverse expressions of mantle convection, represented by subduction zones, spreading centers, plumes, chemical reservoirs, and the various interfacial and boundary layers in the mantle, remains at the center of global geodynamics. Melt production and transport in the mantle and crust are critical steps in this convective engine that lead to surface volcanism. A third cornerstone paradigm with broad application to the brittle lithosphere is the dynamical relationship between faulting and earthquakes. A fourth geodynamic paradigm is the geodynamo, the set of physical and chemical processes by which the geomagnetic field is sustained in Earth's central core. This report also describes some emerging geodynamic paradigms, such as extra-solar planet evolution and the dynamics of the young Earth, which we anticipate will continue their rapid development.

By virtue of their overall success in explaining diverse observations, these geodynamics concepts provide a foundation for much of the solid Earth Sciences, yet they raise a large number of fundamental questions that are still to be answered. In this report, we explain why the following list of questions represent Grand Challenges facing the current and the next generation of Earth scientists. We identify some approaches to their solution, and briefly discuss what resources will be required. We pay special attention to how these Grand Challenge problems fit within the broader context of the Earth System, realizing that an interdisciplinary perspective will become more vital for scientific progress in the 21st century.

Grand Challenges in Geodynamics

1. *Early Days of the Earth:* What processes occurred within the first few hundred million years of its formation that made the Earth habitable today?
2. *Generation of Plate Tectonics from Mantle Convection:* Why does plate tectonics occur on Earth but not in other terrestrial mantles in our solar system?
3. *Thermo-Chemical Evolution of the Mantle and Core:* Cooling of the Earth by mantle convection is the pacemaker for growth and dispersal of continents, volcanism worldwide, and solidification of the inner core.
4. *Tectonics, Water, Climate, and the Biosphere:* The mantle is Earth's largest reservoir, sequestering and exchanging water, carbon dioxide, and other volatiles with the surface environment.
5. *Dynamics of the Continents—Interiors, Roots, and Margins:* How do the continents, with their deep roots, ancient interiors, and deforming margins, accommodate tectonic plate motions?
6. *Intra-plate Volcanism—Causes and Consequences:* The origins of intra-plate volcanism remain deeply controversial, especially the major long-lived, mid-plate hotspots such as Hawaii.
7. *Earthquake Dynamics:* How can geodynamics lead to a better understanding of destructive earthquakes and tsunamis?
8. *Geology of the Core-Mantle Boundary Region:* What geological processes shape the core-mantle boundary, the most fundamental transition in Earth's interior?
9. *Origin of Earth's Changing Magnetic Field:* How does the dynamo process in the core sustain our constantly changing geomagnetic shield?
10. *Alternate Earths: Extra-solar* Planetary Interiors and their Surfaces: Earth-sized solid planets exist outside our solar system; how do we connect astronomical observations to their interior structure and dynamics?

1. Early Days of the Earth

The Challenge

Our home planet has reached its current state through 4.56 billion years of dynamic activity that includes plate tectonics, volcanism, meteorite impacts, mountain building, and erosion, culminating in the rise of life. 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 we know today.

Unresolved Issues

From a geodynamic standpoint, much remains to be understood about the processes and long-term consequences of the early stages of Earth's formation. Fundamental yet unresolved issues include:

- The physical and chemical consequences of planetesimal accumulation
- The behavior of magma oceans—their crystallization sequence, the controls on crystal fractionation, and the dynamic stability of the end product of magma ocean crystallization
- The survivability of structures created by early differentiation

Background

Comparative planetology has advanced the idea that the long-term evolution of a terrestrial planet may be dictated, or at least strongly influenced, by events occurring within the first 50-100 Ma of its formation. Relative to the modern Earth, the energy available for heating Earth's interior was orders of magnitude higher shortly after Earth's formation. The expectation, thus, is a very active early Earth that potentially experienced a variety of irreversible differentiation processes; one clear example being core formation.

Yet we know surprisingly little about the consequences of this early activity. Improved chronologic methods now show clearly that planetesimal-scale melting was occurring within 2 to 4 million years of the formation of the first solids in the Solar System. These very old ages for planetary magmatism indicate both that extinct radionuclides, particularly 26Al, are responsible for the initial stages of planetary melting, and that planetary accumulation likely involved already differentiated objects, not pristine solar system condensates. Both Mars (based on data for meteorites believed to derive from Mars) and the Moon experienced global differentiation events by 4.4 to 4.5 Ga. These initial differentiation events separated core from mantle, formed large portions of still-existing crust, and left large compositional differences in their interiors that survived for over a billion years to influence the composition of younger volcanic products. On Earth, the importance of early events is revealed by core formation and mantle degassing ages that are within tens to a hundred million years of Earth formation. The discovery of increasingly old crustal rocks on Earth (Fig. 1.1) now allows inferences on the state of Earth's surface and shallow interior within half a billion years or less of Earth formation.

FIGURE 1.1: *Images of Earth's oldest crustal rocks and minerals. Right and left panels are photographs of zircons with labeled ion-probe U-Pb dating spots from Jack Hills Australia (Wilde et al., 2001) and the Acasta Gneiss of North-Central Canada (Bowring et al., 1990). The center picture is of the 4.28 Ga "faux-amphibolite" from the Nuvvuagittuq supracrustal belt in northern Quebec (O'Neil et al., 2008).*

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 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 Process of Planet Growth

Terrestrial planet growth is believed to involve the accumulation of smaller planetesimals. Many models of this process make the assumption that when two planetesimals collide, they simply stick together, ignoring the consequences of a high-velocity collision. The potential significance of such collisions for affecting the resulting composition of the growing planet, however, is clearly shown in models of the giant, Moon-forming, impact (Fig. 1.2). Along these lines, a popular model to explain the proportionately large core of Mercury is that a good fraction of Mercury's crust and mantle was removed by a giant impact like that illustrated in Fig. 1.2.

The compositional similarity of Earth and Moon, along with the large angular momentum of the system, led to models that suggest the Moon was formed as the result of a giant impact into a proto-Earth. Dynamic models of this collision now leave us with the somewhat embarrassing result that the Moon indeed can be formed by such a mechanism, but that such a Moon would primarily consist of impactor material, not material from Earth.

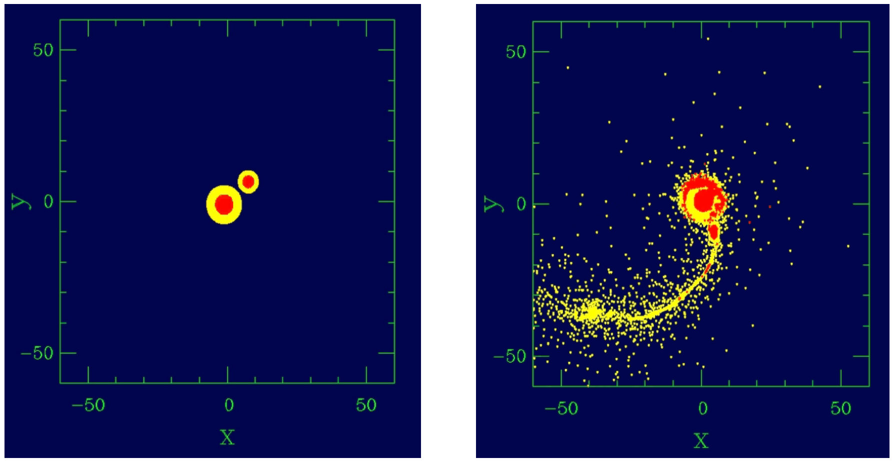

FIGURE 1.2: *Two time-slices in the animation of a glancing impact into the proto-Earth (from (Canup, 2004)). The silicate mantles of the planetesimals are shown in yellow while their cores are red. The first image is slightly before the impact whereas the second is taken after about two orbital rotations 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 (Canup, 2008).*

This issue has given rise to conceptual models that suggest that Earth and Moon chemically equilibrated with one another through a vapor/melt disk shortly after the impact (Fig. 1.3), but such models are at best a suggestion of what might have happened. Our understanding of the events accompanying such major collisions, and their potential consequences for chemical and physical modification of the growing planet, is thin. Geodynamic modeling of these processes is perhaps the only way in which the basic physics of such high-energy collisions can be extracted.

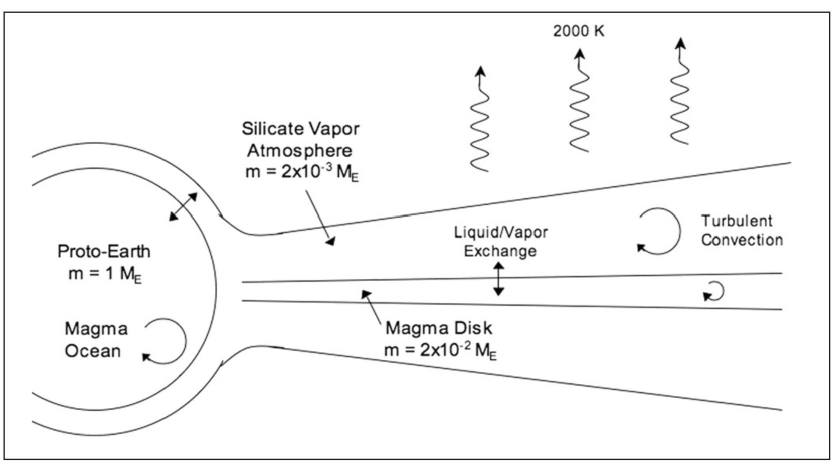

FIGURE 1.3: *A schematic representation of the liquid/vapor disk surrounding the Earth shortly after a giant impact. The key aspect of this model is that substantial chemical exchange between the Earth and the surrounding disk can occur, potentially explaining the similarity in composition between Earth and Moon. From (Pahlevan and Stevenson, 2007).*

The key issue at the heart of this discussion is that most attempts to estimate the bulk composition of Earth start from the assumption that the Earth should be close to Solar, as approximated by the composition of primitive meteorites, in bulk composition. Earth, however, clearly is depleted in volatile elements compared to these primitive meteorites. Whether this reflects nebular sorting of volatile and refractory components, or is the result of the type of violent collisions illustrated in figure 1.2 is a subject of continued discussion. What is clear, is that modeling Earth formation by assuming the gentle and complete accumulation of undifferentiated planetesimals is unlikely to approximate the true process of rapid planet growth that involves very energetic collisions between already differentiated planetesimals. Geodynamic modeling provides essentially the only approach that can investigate the physical consequences of such energetic planet growth. For example, the degree to which incoming planetesimals interact with a growing planet greatly affects the ability to date the timing and mechanism of core formation (Fig. 1.4). Using the Hf-W system to deduce the time of core formation on a large planet, like Earth, depends on

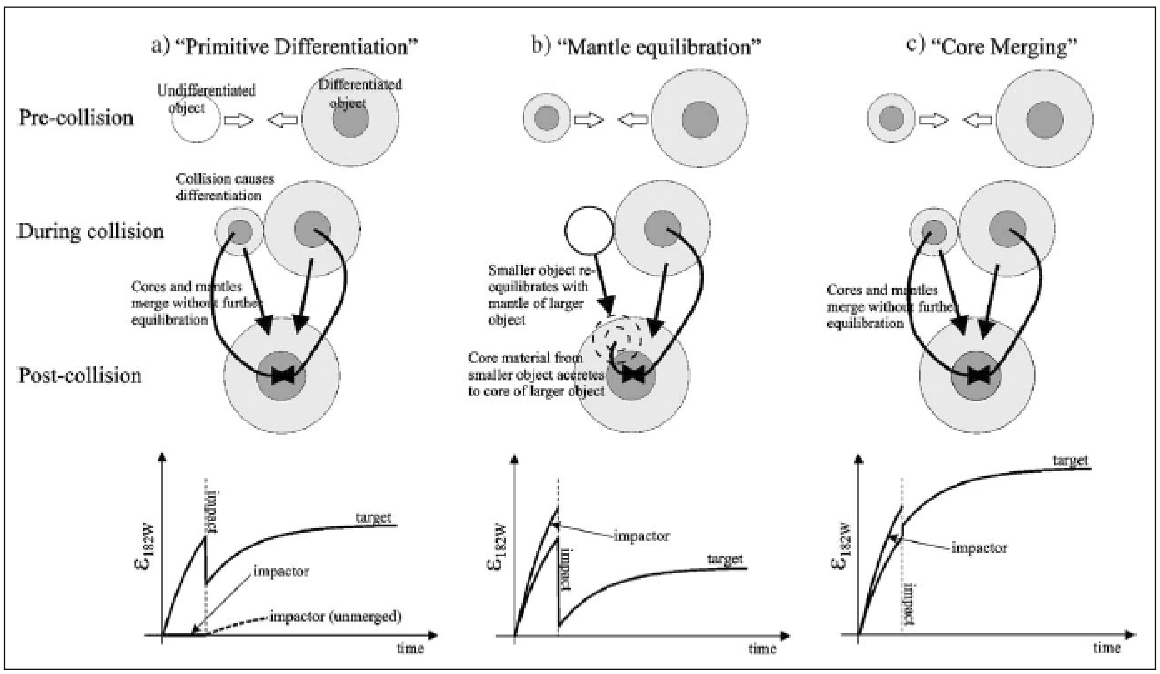

FIGURE 1.4: *Schematic models for core growth during planetesimal accretion and its consequences for the Hf-W isotope system and the interpretation of the information regarding the timing of core formation that it provides. From (Nimmo and Agnor, 2006).*

the degree to which the cores of accumulating, already differentiated, planetesimals, equilibrate with the growing Earth (Fig. 1.4). If no equilibration occurs, then the Hf-W system provides an age that gives only some approximation to the average age of core formation on the planetesimals from which Earth accumulated. If complete equilibration between Earth's core and mantle is maintained during Earth formation, then the Hf-W system dates the time when chemical communication between core and mantle shut down. Giant impact models, for example, suggest that the impacting core plunges rapidly through the Earth to join with Earth's core (Fig. 1.2), implying little, if any, chemical equilibration with Earth's mantle. Whether this is an accurate prediction, or simply a result of the large particle size used in these models, is a question that needs further study. Geodynamics thus has much to contribute to our understanding of the formative stages of the terrestrial planets. Indeed, theoretical investigations often are the primary means to address the type of questions described above as observational evidence of this era of planet formation is nearly absent, and appropriate samples that can address these issues are few.

Early Planetary Differentiation

The combination of rapid planet growth, the presence of short-lived radioactive isotopes of major elements (e.g. ^{26}Al), plus the gravitational potential energy released during core formation provide the energy that drives extensive melting of growing planets. The likely result of quick terrestrial planet formation thus is an extensively melted planet—a magma ocean. Magma oceans were first proposed to explain the globe-encircling plagioclase-dominated crust of the Moon. Magma ocean differentiation of Mars also is believed to be primarily responsible for producing, prior to ~ 4.5 Ga, the wide range in composition of the source regions of Martian meteorites. In contrast, evidence for an analogous early global differentiation on Earth is much more subdued, consisting primarily of abundance patterns of the elements affected by core formation, and by isotopic evidence for early mantle differentiation and atmosphere outgassing.

A potentially important variable in whether or not a magma ocean leads to extensive chemical differentiation of a planet is planet size. We know from iron meteorites that separation of immiscible liquids (in this case, iron from silicate melts) with greatly different densities can be accomplished rapidly, within a million years or less of Solar System formation, even on small planetesimals. Because of its low internal pressures, the crystallization sequence of a silicate magma ocean on a relatively small planetary object like Earth's Moon is reasonably well understood. Like many terrestrial layered mafic intrusions, the Moon provides a good example of the buoyancy-driven separation of relatively dense Mg- and Fe-rich silicates from the lower density Ca and Al-rich mineral plagioclase. On the Moon, this separation was efficient enough to produce a thick flotation crust composed predominantly of plagioclase. On Earth, however, the greater internal pressures introduce many potential departures from the magma ocean evolution seen on the Moon. At issue in understanding the evolution of a terrestrial magma ocean are such basic questions as:

- Does crystallization of a deep terrestrial magma ocean occur from the bottom-up, or from the middle upwards and downwards?
- Are deep melts denser, or less dense, than the minerals that crystallize from a cooling magma ocean?
- What is the sequence of crystals formed?
- Are the densities of the crystals sufficiently higher or lower than the surrounding liquid to cause their separation?
- Does magma ocean crystallization create a buoyantly stable interior or one destined for major overturns with accompanying subsequent differentiation?

Answering these questions likely will require a combination of geodynamic investigations constrained by improved understanding of the petrology of melts in the deep earth and seismic imaging of mantle heterogeneity, particularly at the base of the mantle. One example of a dramatically different evolutionary path for a terrestrial magma ocean involves the possibility of a liquid-solid density crossover at some mantle depth, leading to a basal magma ocean (Fig. 1.5).

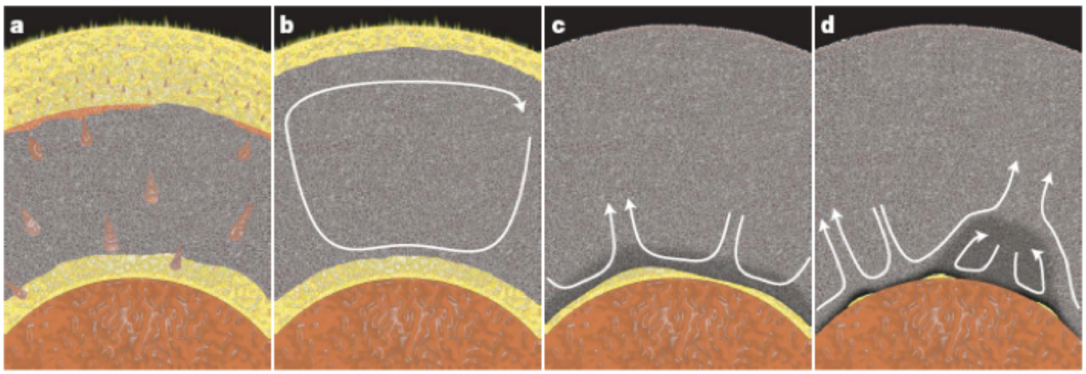

FIGURE 1.5: *Schematic evolution of the initial growth and eventual crystallization of surficial and basal magma oceans (yellow) in the Earth. This model is based on the premise of a deep-mantle density cross over between melt and solid, leading to upward segregation of melts in the upper mantle, but downward migration of melt in the lower mantle. Because heat from the buoyantly stable melt layer at the base of the mantle would be removed primarily by conduction rather than advection, a melt layer like this could stay molten for a considerable fraction of Earth history. Evidence for melt at the base of the mantle is observed in the ultra-low seismic shear wave velocities seen in some regions of the D" layer at the base of the mantle (e.g. (Lay et al., 2004). Figure from (Labrosse et al., 2007).*

Downwards segregation of melt in the deep mantle has a number of interesting consequences ranging from potentially detectable structures at the core-mantle boundary to the formation of a deep analog to the continental crust that would be enriched in incompatible elements, and hence the major heat producing elements U, Th and K. A basal layer with high internal heat generation could substantially alter many aspects of solid earth dynamics ranging from the heat flux leaving the core, to generating a convective style in the overlying mantle driven primarily by bottom, rather than internal, heating. Another aspect of this problem concerns the stability of the crystallization products of a magma ocean. At pressures appropriate for lunar and Martian magma oceans, cooling and crystallization of a magma ocean leads to residual liquids, and hence late-stage cumulates, that are rich in iron and titanium. These iron-rich cumulates are quite dense compared to earlier crystallizing phases. In an undisturbed pile of cumulates, the end product of magma ocean crystallization thus produces dense layers overlying low-density cumulates: a buoyantly unstable result. Such a package will undergo overturn (Fig. 1.6) creating a buoyantly stable layering that will impede further mantle convection until a thermal gradient is restored that will overcompensate for the chemical density of the layers. There is evidence in the degree of isotopic variation in pre-3.5 Ga crustal rocks on Earth for preservation of ancient heterogeneities (formed pre-4.5 Ga). This isotopic heterogeneity was erased between 3.9 and 3.5 Ga potentially supporting this model of vigorous initial differentiation followed by a period of quiescence in the mantle.

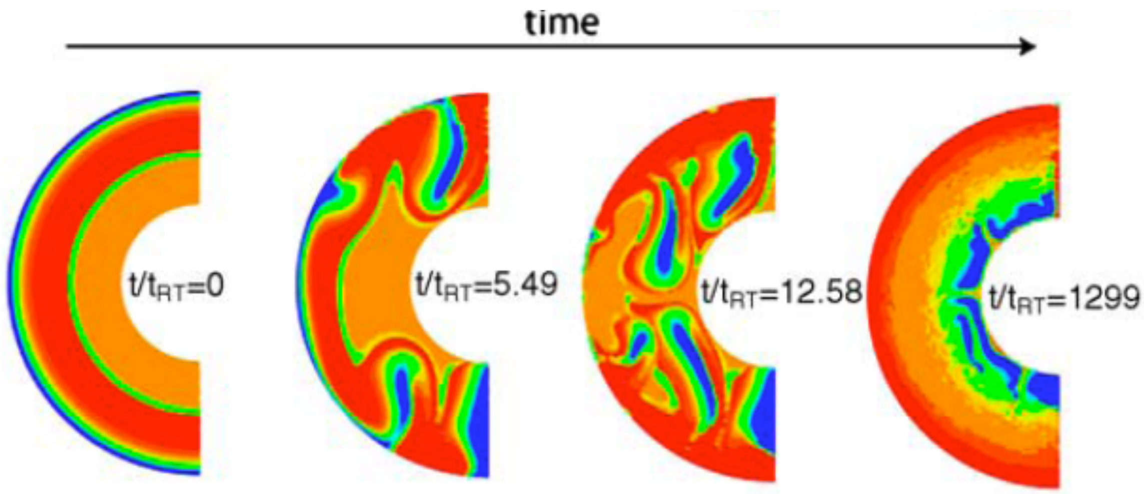

FIGURE 1.6: *Results of geodynamic calculations following the overturn of a buoyantly unstable layering of cumulate minerals formed through magma ocean crystallization. Figure from (Elkins-Tanton et al., 2005). Color coding shows compositionally-induced density with cooler colors reflecting higher density material.*

Many aspects of this type of model need to be addressed, including such basic issues as whether density stratification would form in a terrestrial magma ocean or whether turbulence in the ocean would impede separation of crystals from liquid. The examples provided by Mars and the Moon suggest that planet formation ends with a highly differentiated interior. As discussed below, the continuing dynamic activity of Earth's interior may have diluted the signal of early differentiation, but a variety of recent results, ranging from isotopic evidence for early differentiation to seismic imaging of deep mantle structures that may be remnants of early-formed chemically distinct layers suggest that remnants of early differentiation remain detectable and potentially have major implications for our understanding of the chemical structure and dynamic evolution of Earth's interior.

Long-term Consequences of Early Differentiation

Continent extraction has left an obvious chemical imprint in the portion of Earth's mantle that melts to make the oceanic crust. The oceanic crust shows a complementary depletion in the elements that are particularly enriched in continental crust (Fig. 1.7). Although there remains considerable debate about the rate of continent formation through time, there is little disagreement that this process has occurred throughout Earth's history. Hence, unlike Mercury, Mars and the Moon, almost all of Earth's present crust is a product of the long-term dynamics of Earth's interior. The continental crust, at least that which exists today, is not a product of magma ocean differentiation. The mechanism by which continental crust production and recycling has modified the compositional structure of the mantle has been the subject of a large number of geodynamic models of mantle convection pursued over the past 30 years.

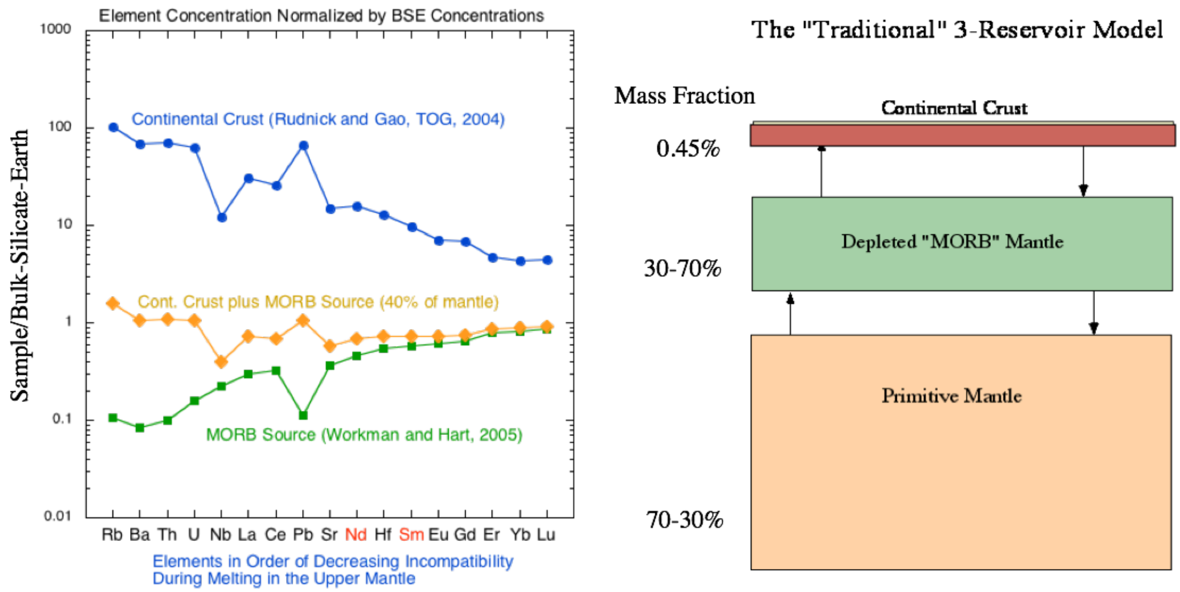

FIGURE 1.7: *The chemical complimentary relationship of continental crust and the mantle source of mid-ocean ridge basalts (MORB). Average continental crust (Rudnick and Gao, 2003) is enriched in the more highly incompatible elements and Pb, whereas the mantle source of oceanic crust (Workman and Hart, 2005) is depleted in these same elements. This relationship, and the assumption that this differentiation began from a "primitive mantle" with concentrations of these elements deduced from comparison with primitive meteorites (Palme and O'Neill, 2003), allows calculation of the relative sizes of these chemical reservoirs within Earth's interior (Allegre, 1982; Hofmann et al., 1986; Jacobsen and Wasserburg, 1979).*

A question of increasing importance, however, is whether the process of continent formation and consequent mantle differentiation acted on a mantle that initially was a homogeneous mixture approximating the average composition of the planet (minus the core). This assumption is implicit in many of the mantle differentiation models pursued since the 1980's. Evidence is building, however, that the "starting mantle" was the differentiated remnant of early Earth differentiation events (Fig. 1.8). Variations in Xe isotope abundances between Earth's atmosphere and mantle indicate changes in volatile abundances in the mantle that occurred while the short-lived radioactive isotopes ^{129}I and ^{244}Pu were still present, in other words, prior to 4.4. Ga. Mantle gases with ^{4}He/^{3}He ratios lower than the atmosphere indicate the presence of relatively undegassed reservoirs in Earth's interior. Although originally associated with "primordial undifferentiated mantle," several recent studies instead indicate that the low ^{4}He/^{3}He mantle is depleted in incompatible elements compared to any estimate of primordial mantle. All terrestrial rocks measured so far have ^{142}Nd/^{144}Nd ratios higher than chondritic. Produced by the decay of 103 Ma half-life ^{146}Sm, the elevated ^{142}Nd/^{144}Nd testifies to production of a high Sm/Nd ratio (or incompatible element depleted) mantle reservoir while ^{146}Sm was still extant, or within a couple of hundred million years of Earth formation.

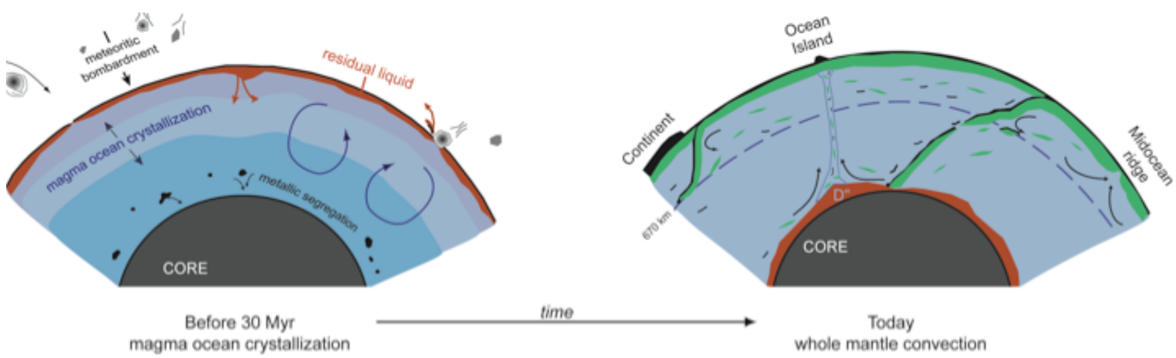

FIGURE 1.8: *Cartoon of an initial magma ocean differentiation of Earth's interior. Subduction of an early-formed crust (red) forms a layer at the core mantle boundary. The still continuing formation of continental and oceanic crust and the partial recycling of the crust through plate-tectonics then superimposes another chemical differentiation on mantle that was already differentiated through the removal of the early-formed crust. This model developed from the observation that all Earth rocks measured so far have a different ^{142}Nd/^{144}Nd ratio compared to primitive meteorites (Boyet and Carlson, 2005). ^{142}Nd is derived from the radioactive decay of ^{146}Sm, which has a half-life of 103 Ma. Because of the short half- life of ^{146}Sm, variation in ^{142}Nd/^{144}Nd testifies to differentiation events that must have occurred within the first couple of hundred million years of earth history (Carlson and Boyet, 2008). This evidence for early mantle differentiation supports previous inferences for early mantle degassing derived from isotopic variations in xenon created by the decay of short-lived ^{129}I and ^{244}Pu (Pepin and Porcelli, 2006).*

All of these observations question the basic assumption that the differentiation of Earth's interior was accomplished primarily through the operation of plate tectonics and continent building over Earth's history. Of critical importance is that a chemically differentiated mantle formed early in Earth's history could have decidedly different physical and chemical properties compared to a "primordial undifferentiated mantle" that would lead to dramatically different dynamic behavior. Some models for early mantle differentiation predict abundances of radioactive heat producing elements in the bulk of the mantle nearly a factor of 2 lower than previous estimates for "fertile" mantle (Fig. 1.9). Because water behaves as an incompatible "element" during mantle melting, the observation that the "undegassed" or low ^{4}He/^{3}He mantle is depleted in incompatible elements could imply that it is also depleted in water, and hence stronger than more water-rich mantle. The point here is that early differentiation could have left the mantle with physical properties quite different from the parameters used for decades to model the dynamic evolution of Earth's interior on the assumption that it was undifferentiated.

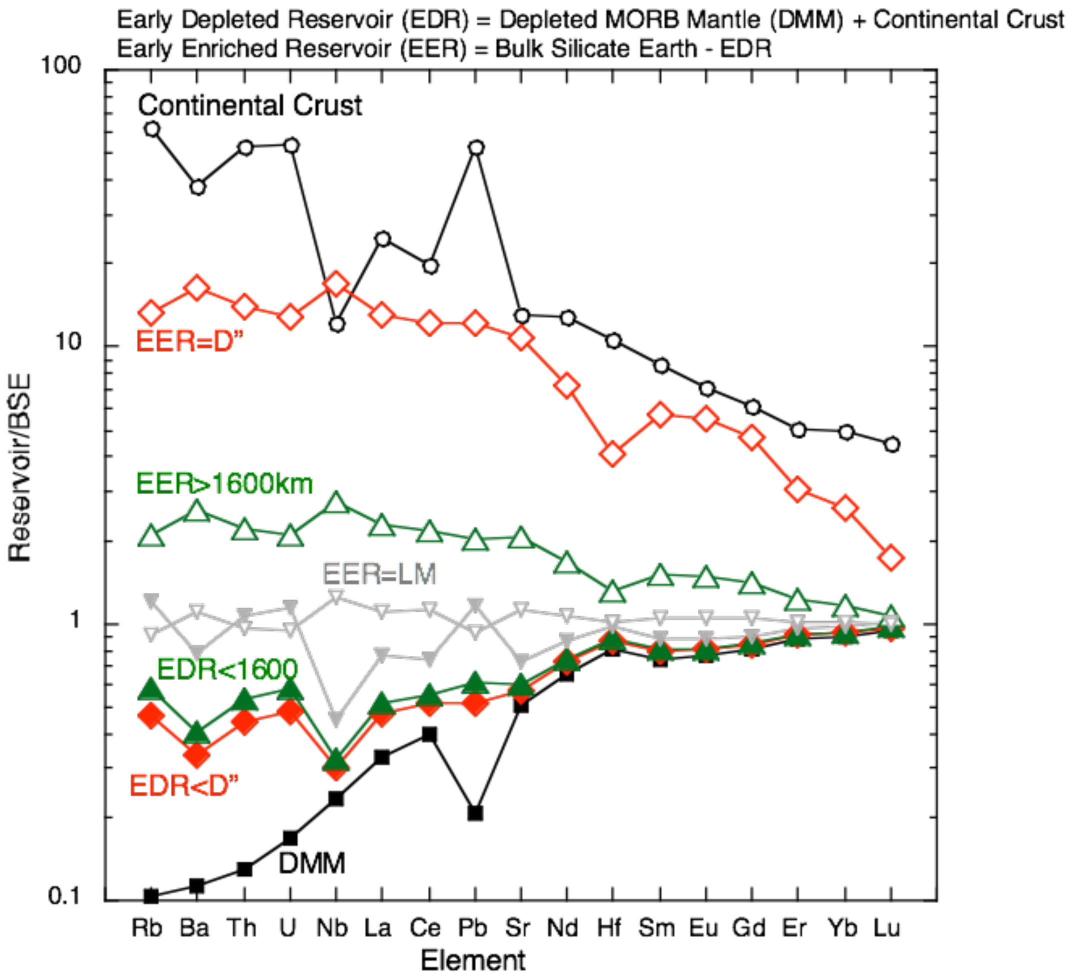

FIGURE 1.9: *Incompatible element abundances, normalized to an estimate of the composition of the bulk-silicate earth (BSE (McDonough and Sun, 1995)) for the depleted mantle that is the source of mid ocean ridge basalts (DMM, (Workman and Hart, 2005)), average continental crust (Rudnick and Gao, 2003), and various models for early incompatible element depleted (EDR) and enriched (EER). The abundance patterns for EDR and EER are a function of the size of these reservoirs, which is unconstrained, so examples are provided for enriched reservoirs that range in size from the D" layer, to the whole mantle below 1600 km depth, to the whole lower mantle below 670 km depth. Figure from (Boyet and Carlson, 2005).*

Another important consequence of early mantle differentiation is the possibility that an incompatible-element enriched complement (the EER shown in figure 1.9) to the generally incompatible element depleted mantle (the EDR shown in figure 1.9) still exists in the deep mantle. Although still speculative, geochemical evidence (e.g. figure 1.8), the suggestion from mineral physics for a melt-solid density cross-over in the lower mantle (Mosenfelder et al., 2007; Stixrude et al., 2009), observations of melting in the D" layer, and seismic observations of the lowermost mantle that apparently require the presence of compositionally distinct materials, all suggest that the lowermost mantle may have properties that lie outside those expected for a homogeneous mantle. Whether the D" layer at the base of the mantle is a pile of subducted oceanic slabs, a chemical interaction zone between core and mantle, or a remnant of early differentiation, is a topic of increasing discussion. Whatever the answer, modeling the deep earth as a homogeneous medium with bulk-earth chemical properties is an increasingly oversimplified approach to an area that shows seismic complexity second only to the crust. The prospect that the deep mantle contains remnants of early differentiation opens a huge parameter space of internal heat production, compositional density, and mineral properties that have not yet been explored in geodynamic models. This is a fertile geodynamics research area with the best prospects to answer the question of how the initial differentiation of Earth may have affected its long-term dynamic behavior.

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2. Generation of Plate Tectonics from Mantle Convection

The Challenge

In the last decade, the holistic hypothesis has emerged that plate tectonics and mantle convection are one in the same, wherein the motion of plates and sinking of lithospheric slabs are simply manifestations of mantle convection. How and why tectonic plates arise and evolve from a convecting mantle, and why this happens on Earth but not other terrestrial planets in our Solar System, are the fundamental questions in the quest for the grand unifying theory of plate tectonics and mantle convection.

Major Milestones

The theory of mantle convection was originally developed to understand the thermal history of the Earth and to provide a driving mechanism for continental drift. One of the major accomplishments of mantle dynamics theory is that convective fluid velocities, calculated in any number of ways, consistently predict the measured scales of plate tectonic velocities, i.e., between 1 and 10 cm/yr. This was in fact inferred even in the 1930s from both gravity and heat-flow measurements and is well known by the force balance on sinking slabs and even the mid-mantle cooling from slabs. That cold sinking slabs seem to be the major expression of convection and major drivers of plate motions implies that the plates are convection. While convective and slab driving forces for plate tectonics are important, understanding how plates self-consistently arise (or why they do or do not arise) from planetary convection has been a major goal in geodynamics. Up until the early 1990s it was believed that since plate-like motion of the lithosphere was essentially discontinuous it could not be predicted or reproduced by fluid dynamical convection theories. However, in the last 15 years or so there has been major progress with fluid dynamical models yielding very plate like motion by incorporating more sophisticated rheological weakening mechanisms, such as brittle/plastic yielding or damage mechanics.

Unlike many theories in cosmology and particle physics, which can predict with significant accuracy the abundance of elements in the entire universe, there is no accepted geodynamical theory that can accurately and quantitatively predict how most plate tectonic motions (ridges, subduction zones, strike slip faults) arise or initiate from a convecting mantle, how plates have formed and evolved through time, when plate tectonics initiated on Earth, why Earth is the only terrestrial planet in our Solar System with plate tectonics, whether Earth's other unique features (liquid water, a stable temperate climate, and life) are causes or effects of plate tectonics, and finally whether we expect to see plate tectonics on the multitude of terrestrial planets discovered in other solar systems. These are the major questions and challenges of the plate generation problem, and they will remain a broad and active area of research for years to come.

Key Questions and Unresolved Issues

Major Questions

- Why and how does Earth have plate tectonics but other planets do not?
- How is plate tectonics self-consistently generated from a convecting mantle?
- What is the link between plate tectonics and Earth's other unique features, i.e., liquid water and life?

Unresolved Issues

- The physics of plate generation: How does mantle convection in combination with rheological feedback mechanisms give rise to plate-like motions? What are the relevant rheological feedbacks?
- Subduction initiation: How does cold still lithosphere go unstable and sink, and if it adopts pre-existing weak zones, how do these evolve into subduction zones?
- How do plates grow and reorganize? How do plate boundaries evolve, die, and reactivate?
- When was the onset of plate tectonics? What are the conditions for this onset? Was early pre-plate-tectonic Earth (if it existed) similar to a non-plate-tectonic planet like Venus?
- What are the conditions for plate tectonics, i.e., presence of water, temperate climate, planetary size?

Background: The Plate Generation Problem

The link between plate tectonics and mantle convection is one of the oldest and most challenging problems in the history of geodynamics. The original theories of mantle convection put forward by A. Holmes in 1931 were developed in the context of explaining continental drift as articulated by Alfred Wegener in 1924. Although plate tectonics is the grand-unifying principle of geology, it is a kinematic theory in that it describes surface motions but not their cause. Mantle convection is widely accepted to be the engine for plate motions since it is a fundamental mechanism for exploiting the energy sources of the Earth's interior, i.e., loss of primordial and radiogenic heat. In recent years it has come to be understood that the plates themselves are a feature of mantle convection in that they are the mobile upper thermal boundary layer of convective cells that thicken as they cool in their migration away from ridges until they are heavy enough to sink along subduction zones. However, there is still no comprehensive theory of how the plates and mantle are related, and in particular how plate tectonics self-consistently arises from a convecting mantle. Both one clue (and one frustration) is that the Earth appears to be the only known terrestrial planet that has plate tectonics in addition to liquid water as well as life, which are all either causative (i.e., necessary conditions for each other) or coincidental. While our planet supports plate tectonics, our ostensible twin, Venus, does not; this remains a leading-order quandary in Earth sciences and to solve it we must understand how and why plate tectonics is generated at all. Of course we have until recently only sampled the few planets of our own solar system and thus the data is sparse; with the advent of extra-solar planetary discovery, this sparseness should be mitigated and perhaps we will find other planets with plate like mantle circulation that will then let us learn more about how our own planet works.

There are of course various qualitative and philosophical questions about how and why plate tectonics forms, evolves and exists, but for these to be predicted or reproduced in a physical theory, one requires quantifiable questions. In short, what are the metrics of plate generation? Two fundamental features of plate-like motion exist for instantaneous motions: these are *plateness* and *toroidal motion*. Plateness is essentially the extent to which surface motion and the strength of the lithosphere is like that for nearly rigid blocks separated by narrow weak boundaries. Toroidal flow is characterized by strike-slip motion and plate spin. Toroidal motion has no direct driving force in buoyant convection (which drives only vertical and divergent motion), however, it has as much energy in the present-day plate tectonic velocity field as the buoyantly driven motion (called poloidal motion). The globally averaged toroidal motion is dependent on the lithosphere's reference frame (e.g., hotspot frame), and the field in general changes through time; however, the toroidal field is a quantifiable and significant feature of global plate motions. Such measurable quantities as plateness and toroidal flow are important for testing the predictions of plate generation theories.

Recent Progress

In the last decade, plate generation models have become increasingly sophisticated, in concert with further expansion and accessibility of high-performance computing. Instantaneous plate-like behavior has been achieved with convection models employing various forms of plastic yield criteria. Incorporation of these laws with the rheological effects of melting at ridges has, for example, lead to the prediction of localized passive spreading zones. Most recently these models have been extended to three-dimensional spherical models, creating the first global models of plate generation from mantle convection.

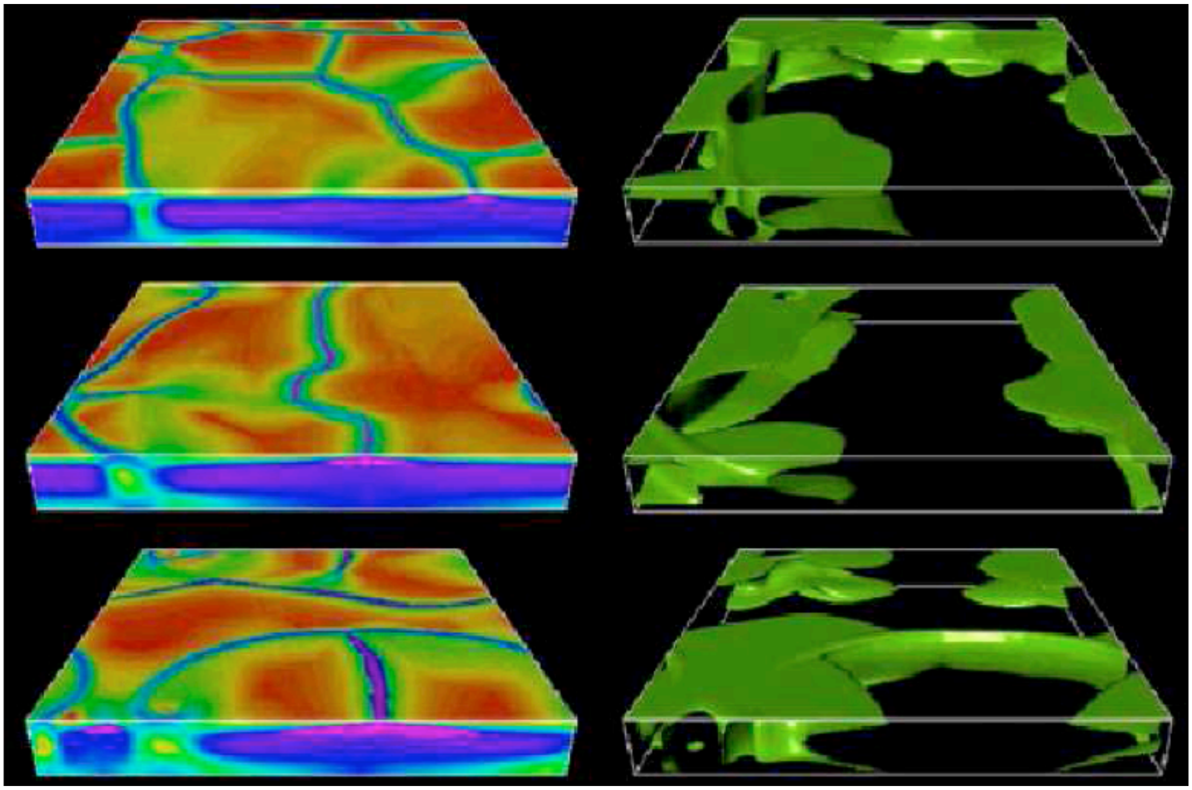

FIGURE 2.1: *Three snapshots at different times from a numerical simulation of plate generation by mantle convection. Here the plate rheology is assumed to be visco-plastic with a viscosity reduction that represents the effects of melting. Plate-like behavior including narrow, passive spreading zones results. Left panels show viscosity contrasts (red=high; magenta=low), right panels show isotherm patterns. After Tackley (2000). Courtesy: American Geophysical Union.*

Weakening mechanisms that depend on properties that persist over some time scale have also been studied. While thermal weakening is a well understood mechanism, thermal anomalies diffuse too fast, and it is highly unlikely that sutures are thermal remnants. Weakening by hydration or as a secondary phase (i.e, by providing pore pressure) is a strong candidate as well, although the mechanism for ingesting water to depth is problematic, and requires mechanisms such as cracking enhanced by thermal stresses. Damage in the form of microcracks and grain-size reduction are also strong candidate weakening mechanisms because of their longevity; the need for shear-localization at significant depth however makes grain-size weakening particularly appealing and has proven very successful at creating plate-like mantle flows. However, grainsize reduction and weakening tend to occur in exclusive areas of deformation space (i.e., weakening occurs during diffusion creep while grainsize reduction coincides with dislocation creep).

Use of both plastic/brittle-yielding and damage theories of plate generation have been used to elucidate the planetary dichotomy between Earth and Venus and the causal link between climate, liquid water and plate generation. Earth and Venus are ostensible twins but Earth has plate tectonics and Venus does not. This is usually attributed to lack of water on Venus, which would otherwise lubricate plate motions; however Earth's lithosphere is likely to be no more hydrated than Venus's because of melting dehydration at ridges. Recent studies have hypothesized that the role of water in maintaining plate motion is not to lubricate plates, but to be an agent for the carbon cycle, which thus allows for a temperate climate on Earth. A cool surface on Earth, according to one hypothesis, causes a larger temperature drop across the lithosphere than would occur on Venus (because of temperature-dependent viscosity), and thus lithospheric buoyant stresses are large enough on Earth to induce plastic/brittle failure, but not on Venus. An alternative hypothesis states that plate-like motion depends on the competition between damage and healing, where a high damage-to-healing ratio promotes plate-like motion, while a lower ratio yields stagnant-lid behavior. A cooler surface temperature inhibits healing while a hot surface promotes healing, thus leading to plate like behavior on a planet like Earth with a temperate climate but not on a planet like Venus. Both hypotheses emphasize that water dictates conditions for plate generation by its modulation of climate and not on direct strength reduction.

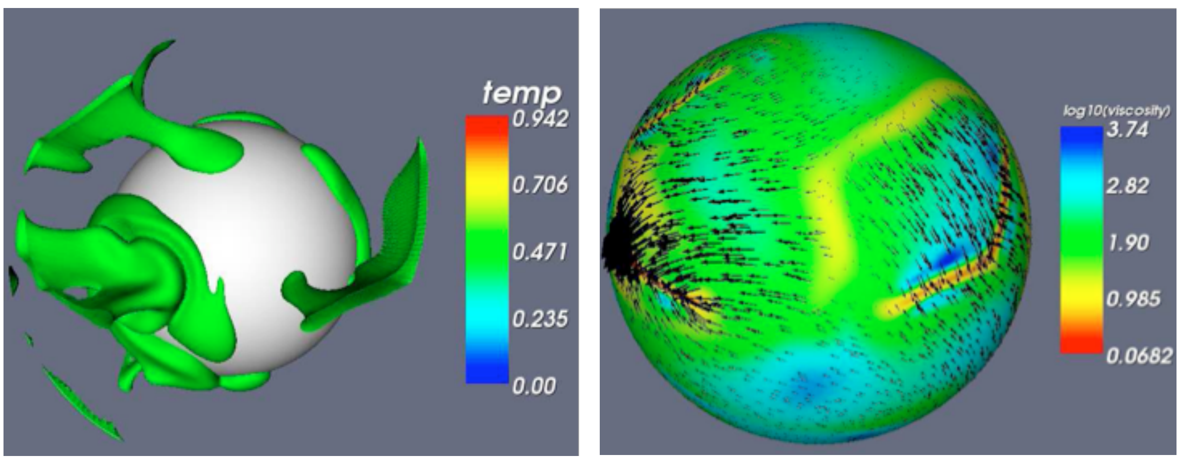

FIGURE 2.2: *Numerical simulation of mantle convection in a spherical shell with assumed plastic lithosphere, yielding plate-like behavior. Left panel shows isothermal surfaces in downwellings. Right Panel shows surface variations in viscosity with surface velocity vectors imposed. A passive divergent weak zone forms between the two major downwelling regions. Adapted from Foley and Becker (2009). Courtesy: American Geophysical Union.*

Finally, subduction initiation continues to be an extremely challenging issue in Geodynamics. The strength of thick, cold, pre-subduction lithosphere is such that it should never go unstable and sink, at least not on geological time scales (or cosmological ones either). Thus how and why subduction zones form remain enigmatic. Mechanisms range from weakening by rifting, sediment loading and water injection, and re-activation of pre-existing fault-zones, all of which have some observational motivation, although fault re-activation might be the most compelling.

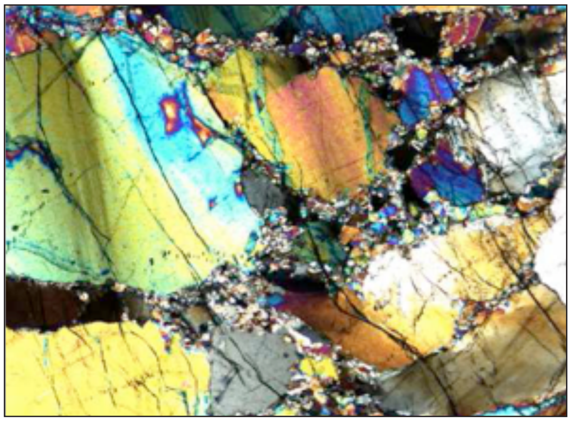

FIGURE 2.3: *Petrographic section of mylonite from the Ivrea shear zone in North West Italy, showing grain size reduction around large grain boundaries. Grain reduction is due to dynamic recrystalization, and is a proposed mechanism for lithospheric shear localization and plate boundary formation. After Jin et al., (1998).*

The Future

The generation of plate tectonics is an expansive problem, and while progress in the last decade has been substantial with regard to developing plate generation theories, the topic is in many ways in its infancy. Several major issues remain unresolved, and new observations will provide first-order tests of plate-generation hypotheses:

Physics of plate generation and plate boundary formation.

Although mantle convection models have been increasingly successful at producing plate-like motion, there is still no consensus on the actual physical or rheological mechanism leading to shear-localization and plate-boundary formation. There is a uniqueness problem in that many such mechanisms can qualitatively produce plate-like motion. Thus other constraints need to be incorporated to test and eliminate proposed rheological mechanisms. For example, while plate-like motion is an instantaneous feature of the present-day Earth, the history of plate motions and the evolution of plate interiors and plate boundaries should provide valuable information to constrain models. In particular, as noted above, a rather popular approach to generating plate-like motion is to invoke plastic rheologies. These give an instantaneous response such that weak plate boundaries only exist while they are being deformed and have stresses above the yielding criterion; once deformation stops they cease to exist. Such plastic behavior thus precludes sutures and inactive weak zones, which are known to be important in that they can become re-activated to form new plate boundaries, especially as subduction zones.

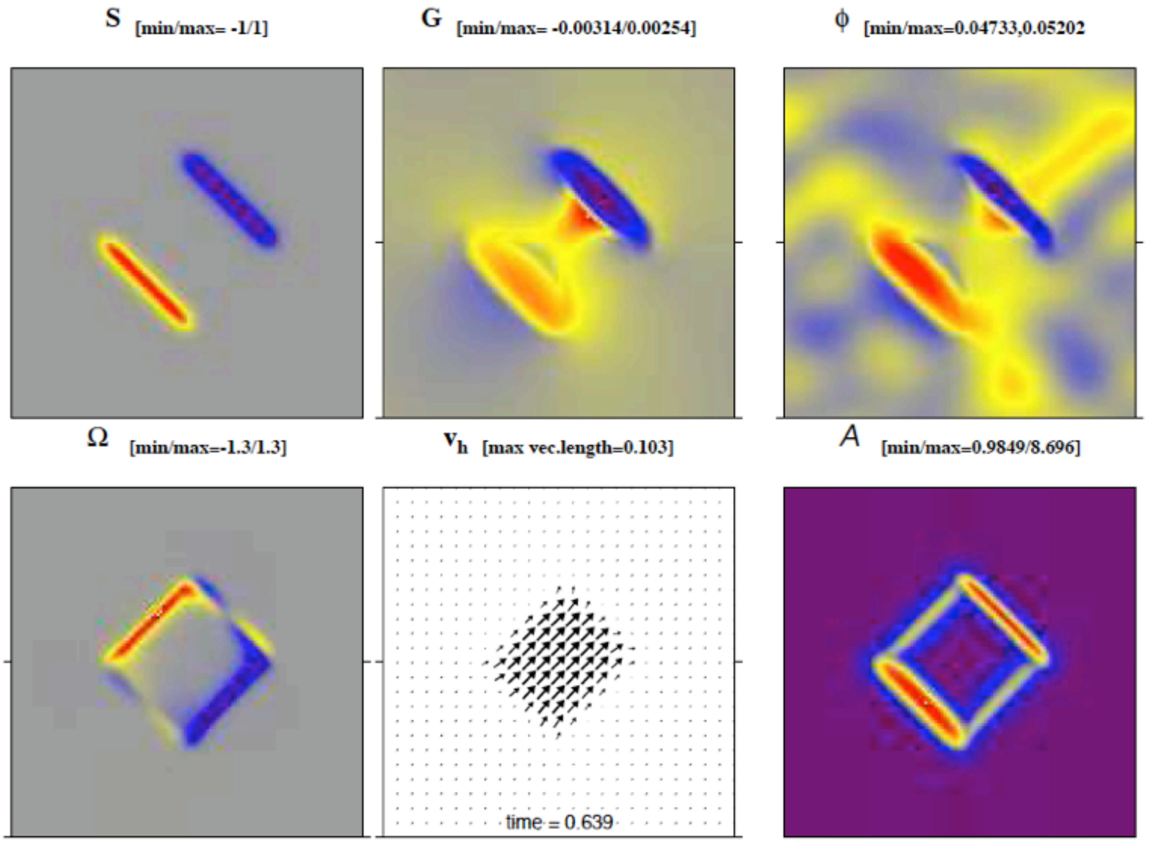

FIGURE 2.4: *Idealized source-sink model of shallow mantle flow including two phases and damage. Damage involves the creation of interfaces in the continuum. For the case shown here, the damage results in grain size reduction. For each panel, S denotes the imposed divergence rate, G is the dilatation rate due to void creation, ϕ denotes void fraction, Ω denotes vertical vorticity (rate of strike-slip shear), v_h denotes horizongal velocity, and A is the inverse grain size. This calculation shows how grain size reduction damage is very effective in creating localization in strike-slip type shear zones and solid body (plate-like) patterns of motion. Adapted from Bercovici and Ricard (2005) Courtesy: American Geophysical Union.*

Role of water and climate.

Earth is unique in the solar system in having plate tectonics and liquid water, which leads to various hypotheses about one needing the other or some feedback existing so that both are sustained. For example, liquid water is supposedly needed to lubricate plate tectonics, while plate tectonics is thought necessary to provide a stable climate that permits liquid water. However the mechanism by which liquid water promotes plate tectonics is not at all clear. An appealing assumption is that water facilitates faults and localization by various means such as hydrated sediments, reduction of friction by pore pressure and serpentinization. Yet such weakening and localization needs to occur across the entire cold lithosphere, i.e., approximately 100 km, and thus transporting water to such depths and/or holding open pores at the associated pressures is problematic. As noted above, recent studies comparing Earth and Venus suggest that water facilitates plate motion by stabilizing surface temperatures rather than by rheological weakening. However, these hypotheses need to be tested by examining other planets and epochs in Earth's past.

Subduction initiation and strength

Based on its temperature and creep rheology, the Earth's lithosphere is cold and stiff and should not be moving at all, and least of all foundering and sinking into the mantle where it is thickest and stiffest. Simple convection theories predict the Earth should be in a "stagnant lid" regime in which the lithosphere does not participate in the under-lying mantle convective circulation. However, the lithosphere does indeed subduct and sinking slabs are the driving force of mantle convection. How subduction zones initiate from a cold stiff lithosphere is a long-standing and unsolved question and has been addressed by various approaches of pre-weakening the site of the subduction zone as discussed above. Given the difficulty of initiating subduction in pristine lithosphere, the presence of pre-weakened zones or dormant plate boundaries illustrates the importance of understanding plate-generation history and evolution. The role of subduction zone resistance strength also remains an important question. The force balance on slabs sinking in the viscous mantle predicts plate velocities quite well; however, the resistance on the slab might in fact arise from the bending of the plate through the subduction zone and the velocities might be independent of mantle viscosity entirely. This would mean that plate velocities would be nearly insensitive to changes in mantle temperature thus suppressing self-regulation and allowing the mantle to retain its primordial heat; this has important implications regarding the thermal and geochemical history of the Earth.

The onset of plate tectonics.

Whether the Earth always had plate tectonics is unknown, and if it did not, then the conditions for the onset of plate tectonics is a crucial piece of information for understanding how plate tectonics formed and exists today. Paleomagnetic plate reconstructions have for many years struggled to go deeper than the Cambrian, but in recent years reconstructions have pushed into the early Proterozoic era, although even this might not be deep enough in time. Moreover, considerable resolution of plate boundary structure and plate motions will be needed to resolve the nature of plate motions in the deep past. Geodynamical models of plate generation should necessarily provide predictions of this onset by thermal history models and/or temporally evolving simulations with the hypothesized plate-generation physics; as the observations are increasingly refined they will continue to test and again eliminate plate-generation mechanisms and hypotheses.

Plate reorganizations and growth.

Further but perhaps more nebulous tests of plate generation theories are the prediction and reproduction of continuous changes like plate reorganizations and plate growth. While a "critical point" like onset of plate tectonics is conceivably a distinct and predictable event, plate evolution needs to be quantified so that theoretical models can be tested rigorously. For example, the history of plate-size distributions (mean size, variance, etc.) might be useful although the numbers are never large. The history of toroidal and poloidal motion is also possibly important.

Age of subduction.

The convective picture of plate motions would have plates subduct when they get old, cold and heavy. However, the sea-floor age distribution implies that subduction rate is independent of plate age, such that the age of plates at subduction zones is distributed from nearly 0 age (i.e, subducting ridges), to the oldest ages of roughly 200 Myrs. This enigmatic observation remains a fundamental feature of the plate-mantle system and provides another constraint and test for plate-generation studies.

The Frontier

The frontier of plate generation theory is at least several-fold. Plate-generation hypotheses can be tested and further developed by examining their predictions of plate evolution through Earth's deep history, i.e., the earliest onset of plate-like motions, plate evolution (plate growth and plate re-organizations and reversals, plate boundary formation, dormancy, re-activation) and its influence on thermal evolution of the Earth (both interior cooling and how plate and continental configurations affected climate, by, for example, establishing conditions for Snowball Earth events). Secondly, the coming decades will see plate-generation theories tested with data on other terrestrial planets, icy-satellites and extra-solar planets and super-Earths. In short, plate generation models must be tested through the 4th dimension of time by approaching information on the evolution of plate tectonics, and treat the multitude of planetary conditions that facilitate or inhibit plate tectonic activity.

The physics of plate generation is still not fully understood, although much progress has been attained in the last decade or more. Plastic/brittle treatments have yielded instantaneous Earth-like models but are unlikely to be able to model temporal evolution, especially due to dormant fault reactivation. Self-weakening theories, such as damage theories, are still grappling with the state variable that cause weakening. If grain-size is the major agent of weakening, then there is much left to be understood such as how grain-size distribution changes during localization events, and how weakening during diffusion creep and grain-reduction during dislocation creep can mix or co-exist. Still, there may be other, yet undiscovered physics of weakening and shear-localization.

The link between Earth's unique features, i.e., plate tectonics, water and life, remains a tantalizing question. The causal link between plates and water is conceivably through their role in stabilizing climate (i.e. they are both required to stabilize climate and both only exist in a stable climate). It is possible that life is just a passive consequence.

Alternatively, biological activity plays an important role in the carbon cycle. Formation of carbonates in the sea is biologically modulated. Moreover, the rise of oxygen during the Archaean was also coincident with massive photo-synthetic activity that tied carbon up into biomass and was thought to cause extreme excursions of the climate. Exploration of these links is in the end paramount for understanding the entire Earth system, i.e., how the Earth's interior, oceans, atmosphere, and biosphere interact.

Research Disciplines, Directions and Tools

The plate generation problem is intrinsically interdisciplinary, since it involves collaboration between theoreticians, numerical modelers, experimentalists, and observers. Future researchers and students in geophysics and geodynamics will need to be well versed in several areas, including the following:

- Material physics, condensed matter physics, complex and soft-matter physics (e.g., grain coarsening and reduction), all integrated into continuum physics.
- High-resolution numerical models to resolve shear-localization and small-wavelength properties of shear-zones advected through time.
- Mineral physics experiments to measure, for example, weakening and slip mechanisms, and the evolution of grain-size distribution.
- Plate reconstructions into deep time, with enough spatial and temporal resolution to infer not just bulk plate shapes and continental configurations, but also plate boundary history and re-activation.
- Seismic analysis of incipient plate boundaries, including anisotropy, to determine fabric and plate motions.
- Increasingly detailed observations of extra-solar planet surfaces and their chemistry.

Requirements for Sustained Progress

The development of plate generation theory is on-going. While better theoretical and computational models are necessary, these models need further experimental and observational tests to constrain and test them. In short, the key requirements for future progress are as follows:

1. Improved physical theories of localization require further integration of materials sciences with continuum physics, but these also must be done in conjunction with mineral physics experiments. The complexity of these models will always require more powerful high performance computing and parallel computing clusters. Progress in computation will be aided if parallel programming did not involve so much over-head, and instead scientists could rely on parallel compilers in the same way that super-computers in the 1990s relied on vector compilers.
2. Testing of models requires deep time observations of plate motions (data in 4th dimension). Paleomagnetic evidence of plate motions in deep-time, including the deep Precambrian is simply labor intensive and involves extensive and difficult field programs.
3. Planetary and extra-solar planetary observations will be crucial for continuing to test our understanding of how the Earth works in general. In the coming years, geodynamicists need to work with the astronomical community to help infer the nature of other planets and the conditions under which they might sustain plate tectonics, as well as temperate climates and life.

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3. Thermo-Chemical Evolution of the Mantle and Core

The Challenge

The large-scale dynamics of the mantle is a giant engine, transporting primordial heat as well as heat produced by radioactive decay from the deep interior to the surface. By far the most important process in this engine is mantle convection. Over long time scales, mantle convection cools the whole of Earth's interior. As by-products, continental and oceanic crust are generated, deformed, and consumed, and compositional and isotopic heterogeneity is created and re-mixed. The pace of mantle convection is reflected in the level of activity of near-surface phenomena such as continental deformation, sea level changes, earthquakes, and volcanoes, as well as the activity of the geodynamo and the growth of the inner core. Here the grand challenge is to understand the operation of this giant heat engine over geologic time, and how it has controlled the present-day structure and composition of the Earth.

Milestone Accomplishments

The Standard Thermal Evolution Model

A simple global energy balance based on subsolidus mantle convection with radioactive heat sources and heat from the core has led to a standard evolution model, which predicts monotonic cooling of the whole Earth by several tens of Kelvins per billion years, with a more-or-less uniform decrease in tectonic activity over geologic time. The rate of energy release predicted by the standard model is sufficient to generate the continental crust, drive plate tectonics, and maintain the geodynamo. A key concept in the standard model is that mantle convection is the primary thermostat for the Earth as a whole, because of the buffering effect of the strong dependence of subsolidus creep viscosity of mantle rocks on temperature.

Variable Plate Tectonics and Continental Growth

Earth's lithosphere can be divided into stable continental cratons, tectonically-active plate margins, and relatively newly formed ocean lithosphere. A pattern is evident in plate tectonic history that involves the opening and closing of ocean basins, changes in the length of the global system of ridges and trenches, and the aggregation and dispersal of large blocks of continental crust. This pattern, traditionally called the Wilson Cycle, has recurred over time scales of several hundred million years, and is linked to long-term oscillations in sea level, major orogenic (mountain building) events, variations in seawater chemistry, and the level of magmatic activity on the continents. The dispersion of the continents following the breakup of the super-continent Pangea are the latest stages of this pattern. The contrast between the relatively simple evolution of oceanic crust and the longer, more complex history of continental crust accounts for the vast differences in age patterns of the two types of crust. Geochemical evidence indicates that this tectonic regime extends back to 3.5 Ga at least, and accounts for most of continental crustal growth.

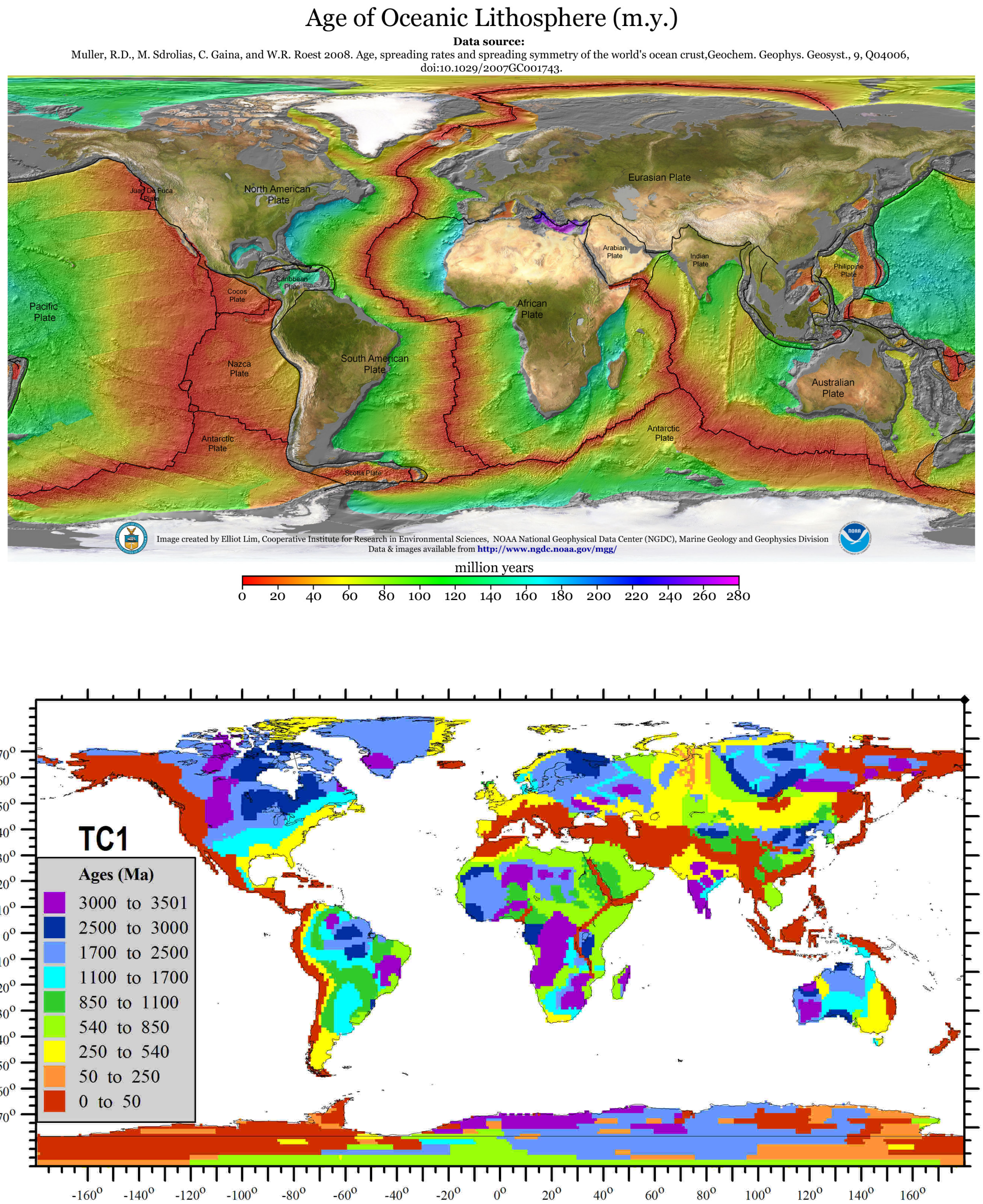

FIGURE 3.1: *Contrasting ages and age patterns of continental versus oceanic crust reflect their different evolutionary histories. Top: oceanic lithosphere (and crust) ages with plate boundaries (from Muller, et al., Age, spreading rates and spreading symmetry of the world's ocean crust, Geochem. Geophys. Geosyst., 9, Q04006, 2008). Bottom: continental crust ages in 1 degree blocks (from Artemieva and Mooney, Geophys. Res., 106B, 16387-16414, 2001).*

Growth of the Inner Core

The solid inner core is the most remote part of the Earth, and would seem to be an unlikely place to find a record of the evolution of our planet. Among the primary subdivisions of the Earth, the inner core appears to be the youngest and the most rapidly growing. Considerations of the rate of heat loss from the core indicate the inner core has grown to its present 1220 km radius in less than 2 Gyr and possibly within the past 600 Myr. As a by-product of its relatively rapid growth, the inner core acquired a remarkable amount of structure. Seismic imaging has revealed a complex pattern of heterogeneity in the inner core, including textural differences between the deepest part of the inner core and regions closer to the inner core boundary (ICB) where there is evidence of an east-west hemispheric dichotomy, which preserve a record of its growth.

Major Unresolved Questions

The milestone accomplishments described above provide starting points for deciphering the evolution of Earth's interior, but in fact there are many more “unknowns” than “knowns” in this subject. Fundamental questions that geodynamics can address include:

- Was the thermal evolution of the Earth actually monotonic cooling, or were punctuated events also important?
- How far back in time have large-scale mantle convection and plate motions dominated global tectonics?
- What style of tectonics dominated prior to plate tectonics?
- How continuous is the circulation with depth in the mantle?
- Are there long-lived chemical reservoirs in the mantle?
- Where are these mantle reservoirs located, and how are they preserved?
- Where are radioactive heat-producing elements concentrated in the crust, mantle, and core?
- Is there a “Wilson Cycle” in mantle convection?
- By what processes and at what rates is continental crust produced?
- What is the present-day rate of continental crust consumption, and has it varied in the past?
- What is the magnitude and pattern of heat flow from the core to the mantle?
- How old is the solid inner core?
- What is the evolutionary significance of inner core heterogeneity?

Background

Monotonic versus episodic mantle evolution

According to the standard model, if the mantle temperature were to increase for any reason, its creep viscosity would drop and mantle convection would become more vigorous, thereby forcing the temperature back to its previous level. Conversely, were the mantle temperature to suddenly drop for any reason, its viscosity would increase and mantle convection would seize up, preventing further cooling. This feedback between temperature and convection tends to stabilize mantle dynamics, leading to the prediction that mantle history consisted of a slow, secular decrease in its temperature, accompanied by a more-or-less uniform decrease in convective vigor.

However, monotonic cooling seems at variance with geologic history, which offers abundant evidence of more catastrophic episodes than the standard model seems to allow. Some examples of seemingly global catastrophic process include rapid continental growth episodes, large igneous provinces, massive volcanic structures on the sea floor and on continents, long stable geomagnetic superchrons, and past global climate instabilities. A fundamental issue here, still unresolved, centers on the importance of these extreme events in the evolution of the Earth as a whole. Here it seems that the standard model is perhaps too limited for satisfactory explanations for many of the important events in the geological record.

Very early in Earth's history, mantle dynamics was probably dominated by impacts related to the accretion process, especially giant impacts. But, what style of tectonics prevailed as accretion became less important? Several mechanisms have been identified that could prohibit early plate tectonics, when the mantle was hotter but still solid, most of these related to the production of thicker ocean crust. Without plate tectonics the lithosphere behaves as a single plate, or more properly, a stagnant lid, below which mantle convection sluggish and the amount convective heat transfer is relatively small. Far less energy is available this regime for crust production, mountain building, earthquakes, and tectonic interaction with the atmosphere and ocean in general. Single plate terrestrial planets such as Venus have evolved along very different trajectories than the Earth, largely for this reason. Accordingly, it is vital to determine if the Earth was ever in such a regime, and if so, when and why.

Mantle Reservoirs

Another enduring issue is the capacity of the mantle to sequester chemical and isotopic heterogeneity in reservoirs. Over the past four decades, this subject has taken the form of an interdisciplinary argument over the continuity of mantle convection with depth. Evidence from mantle-derived isotopes indicates the mantle may be chemically layered, with a depleted upper mantle above a less depleted lower mantle. The alternative interpretation, favored by many geodynamicists, is that the mantle circulation is either wholly or at least partially continuous with depth. Although it often called "whole mantle" convection, this model does acknowledge that the transition zone between upper and lower mantle offers some resistance to mantle circulation, and in fact appears to arrest or stall many subducted slabs. The impediment to flow provided by the transition zone, the 660 km discontinuity in particular, possibly leads to episodic transfer of slab-derived material into the lower mantle, which could ad variability to the secular trend implied by the standard global cooling model. How to reconcile the geochemical evidence favoring isolated mantle reservoirs, seismic evidence for slab material in the lower mantle, and geodynamical models in which the behavior of the mantle is best explained with more continuous circulation, remains at the heart of this controversy.

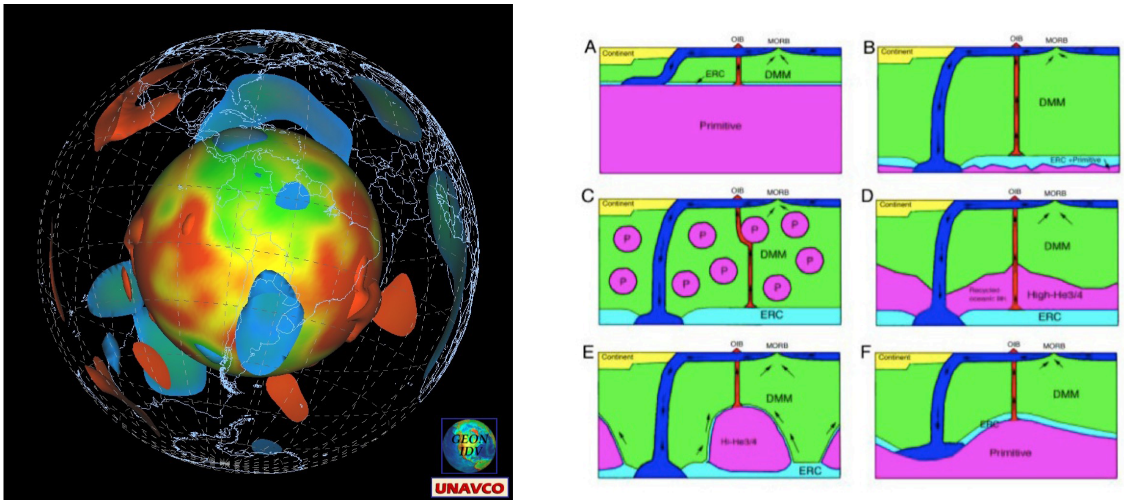

FIGURE 3.2: *Mantle seismic heterogeneity versus mantle chemical reservoirs. Left: Observed lower mantle seismic shear wave heterogeneity, from Harvard tomography model S362D1. Blue, red = high, low velocity regions, respectively. Shear wave velocity heterogeneity is related to temperature and compositional variations, which provide that buoyancy forces that drive mantle convection. [Courtesy: GEON UNAVCO]. Right: Various proposed models for the location of mantle chemical reservoirs and their relationship to mantle convection. Blue denotes oceanic plates and subducted slabs; red denotes thermal plumes; purple denotes primitive mantle. Abbreviations: DMM=depleted mantle; ERC=enriched recycled crust. (A) Layered mantle model; (B) homogeneous mantle with heterogeneous D"-region above the core-mantle boundary; (C) Primitive blobs model; (D) Complete recycling model; (E) Primitive piles model; (F) Deep primitive layer model. [Courtesy: P. Tackley].*

The connection between geodynamical processes and whole-Earth chemistry are obvious at the most general level, but the specifics have proven to be elusive and controversial. Mantle convection and plate tectonics are efficient at chemical transport and mixing, and the chemical fingerprints of lavas derived from mantle rocks offer clues about these processes, as well as evidence for the early state of the Earth.

Low abundance trace elements show systematic variations between volcanic rocks from different tectonic settings. Lavas erupted at midocean ridges for example differ in systematic ways from lavas erupted at volcanic hotspots such as Hawaii and Iceland. There are also systematic differences in lavas along a midocean ridge, as well as between different ridge systems. Helium isotopes indicate parts of the mantle have retained their inventory of volatiles, whereas other parts of the mantle have been degassed. The challenge here is to sort out these abundant chemical clues in terms of a dynamically consistent picture of the present-day mantle structure and its evolution.

Mantle Effects in Environmental Change

The interaction of the mantle with surface environments occurs through a mixture of volcanic activity, exchanges of mass and heat at plate tectonic spreading centers, and through subduction processes at convergent plate boundaries. We have a general outline of how this cycling process works, but we lack many critical details. For example, we know that volcanism adds to the inventory of oceanic and continental crust, injects water, carbon dioxide and other gasses into the atmosphere-ocean and the shallow subsurface environments. Deformation of the continental and oceanic crust connected with plate motions then provides the topographic gradients for physical and chemical erosion processes, by which sediments are altered and transported to convergent plate boundaries, where they are re-cycled into the mantle.

Volcanic activity and hydrothermal systems continuously supply water and CO_2 to the oceans, atmosphere and crust. Most of this occurs at mid-ocean ridges in connection with sea-floor spreading and the magmatism that creates the ocean crust, so that the volatile flux from the mantle is directly proportional to plate tectonic activity and is closely linked to the vigor of mantle convection. The exchange processes that operate in association with subduction zones are not well understood. Subduction zone volcanoes account for nearly all explosive eruptions, and also account for much of the production of continental-type crust. Accordingly, their role in shaping the habitable environment is far out of proportion to their part in the global energy budget.

The vast size of the mantle ensures that huge quantities of such volatiles can be stored in the Earth's interior. Abundant water is expected to have a substantial influence on mantle dynamics, by virtue of its reduction in the creep strength of mantle rocks. Even more directly relevant to plate tectonics, water in sediments can lubricate subduction shear zones and it also reduces the melting points of mantle minerals, leading to enhanced magmatism below convergent plate boundaries.

The Earth's interior is also a critical element in the global carbon cycle. Here the main issue is the flux of carbon from the interior into the surface environment. Most of the Earth's carbon is stored in rocks, and surprisingly perhaps, most of that is found in the mantle and even the core. It is estimated that the total carbon content of the mantle is nearly one million times larger than the present-day atmosphere, for example. Most of the mantle carbon is bound up in calcite ($CaCO_3$), high pressure carbonates and other minerals, and the plate tectonic magmatic processes provide the mechanisms for transferring this carbon to the atmosphere, while subduction processes provide the main mechanism for its return to the interior. Understanding this part of the global carbon cycle is vital to unraveling cause from effect in the record of long-term climate changes.

Growth and Cycling of Continental Crust

Continental crust now covers 41% of Earth's surface, 70% of which is above present-day sea level. With its great antiquity, continental crust records most of Earth's chemical and thermal evolution, back to nearly 4 Ga. The major geodynamical questions regarding the development of continental crust concern the rates and modes of its formation, its selective preservation, as well as the rates and modes by which it is recycled into the mantle.

Much of present-day continental crust formation takes place through calc-alkaline magmatism near convergent plate margins, part of the process known as the "subduction factory." Subduction zone magmatism involves the exchange of mass and heat between downgoing crust and its upper mantle environment, and has likely been a major source of continental crust as long as plate tectonics has been active. The standard model of Earth's evolution predicts a monotonic increase in the mass of continental crust, with fastest growth rates corresponding to shortly after the onset of plate tectonics, beginning perhaps around

3.5 Ga. Relatively minor variations in this growth history are allowed for, during the phases of the Wilson cycle.

There are, however, other large masses of continental crust whose provenance is not easily tied directly to the subduction factory. Evidence suggests that this crust may have formed away from convergent plate boundaries, during relatively short intervals called “super crust-forming events,” possibly related to extremely high levels of mantle plume activity. How the resulting terranes (oceanic plateaus, basaltic underplatings, etc.) were incorporated and selectively preserved in stable cratons in the continental crust remains an open geodynamics question.

Evolution of the Core

Although the metallic core is vastly different from the silicate-oxide mantle in terms of composition, state, and dynamical properties, the evolution of two regions are nevertheless closely linked. In several important respects, the mantle controls the core, by limiting the heat flow at the core-mantle boundary and also through its controlling influence on Earth’s rotation. The present-day heat loss from the core is highly uncertain, with estimates ranging from 4 TW to as high as 18 TW.

The core is mostly iron with 5-15% light elements, an uncertain mixture of O, Si, S and possibly others. The liquid outer core is enriched in these light elements compared to the solid inner core. Secular cooling of the core results in freezing at the inner core boundary, growth of the solid inner core and partitioning of the light elements into the outer core. Together with thermal buoyancy directly generated by heat loss to the mantle, inner core growth adds thermal and compositional buoyancy to the liquid outer core, energy sources for the geodynamo.

The age of the inner core reflects the rate of core cooling and also the energy available for the geodynamo. Current age estimates for the inner core range from 4 to 0.5 Ga, and depend on poorly constrained dynamo properties such as its Ohmic dissipation. Radioactive heat sources in the core are another controversial issue. Although uranium and thorium have been proposed, the leading contender is ^{40}K, by virtue of its affinity to sulfur. However, the amount of ^{40}K in the core is essentially unknown.

Beyond its role as a heat source for the mantle, understanding the evolution of the core is important for its own sake. Core formation was a defining event early in Earth’s history, affecting the entire planet. This event, superimposed on later events, has governed the subsequent evolution of the core, and may be preserved in the solid inner core. In addition, the geodynamo process, a direct by-product of the core evolution, provides us with a way to track the core history, using the paleomagnetic record.

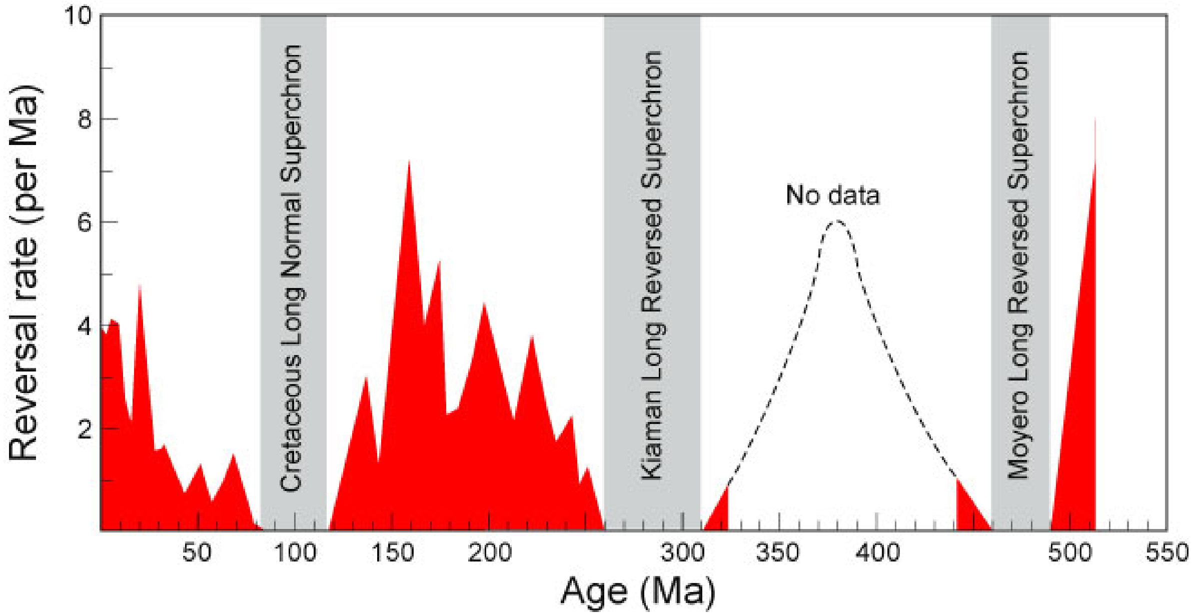

FIGURE 3.3: *Paleomagnetic evidence of core evolution. Changes in the average rate of geomagnetic polarity reversals over Phanerozoic time, 0-550 Ma, from Courtillot and Olson (2007). The existence of three long magnetic superchrons (shaded) and the sustained increase of polarity reversal frequency over the past 100 Ma suggest time-variable control of the core by the mantle.*

In addition to the large heat flow from the core to the mantle, there may be ongoing chemical exchange between these regions. Partitioning of Osmium Os isotopes (decay products of Re and Pt) and also tungsten ^{182}W (decay product of Hafnium ^{182}Hf) have already been proposed as tracers of core-mantle mass exchange. Here the twin challenges are first, to identify trace element or isotopic signatures in mantle-derived rocks that are unique to the core, and secondly, understand how they are transported from the core to the near surface.

Inner Core Tectonics

The inner core is expected to have radial gradients in the concentrations of the light elements such as O, S, and Si acquired during solidification. Its actual solidification rate is probably non-uniform, however, since removal of heat from the ICB is expected to be greater near the equator compared to other latitudes, a consequence of the rotational constraints on fluid motions in the outer core. An overarching question is: did these effects conspire to produce the heterogeneous inner core we see today? It is generally thought that the equatorial solidification combined with thermal convective overturn produced a nearly uniform solid texture when the inner core was very small. The situation may have changed as the inner core approached its present-day size, however, and its growth became laterally heterogeneous. Interpreting the three-dimensional structure of the inner core is a genuinely difficult multi-physics problem. It is important however, because of the new perspectives it can yield on deep Earth history.

The Future

These new developments in Earth's interior evolution present an opportunity to extend geodynamic modeling far beyond its traditional boundaries. The wide range of physical processes involve couplings between the behavior of different parts of the Earth, for example the thermal evolution of the core controlled by the convecting mantle, and the dynamics of the lithosphere, through the development of plate boundaries, exerts control on mantle convection. Exploring these couplings within the framework of Earth's evolution is an especially daunting challenge, however, because of the enormous time intervals involved.

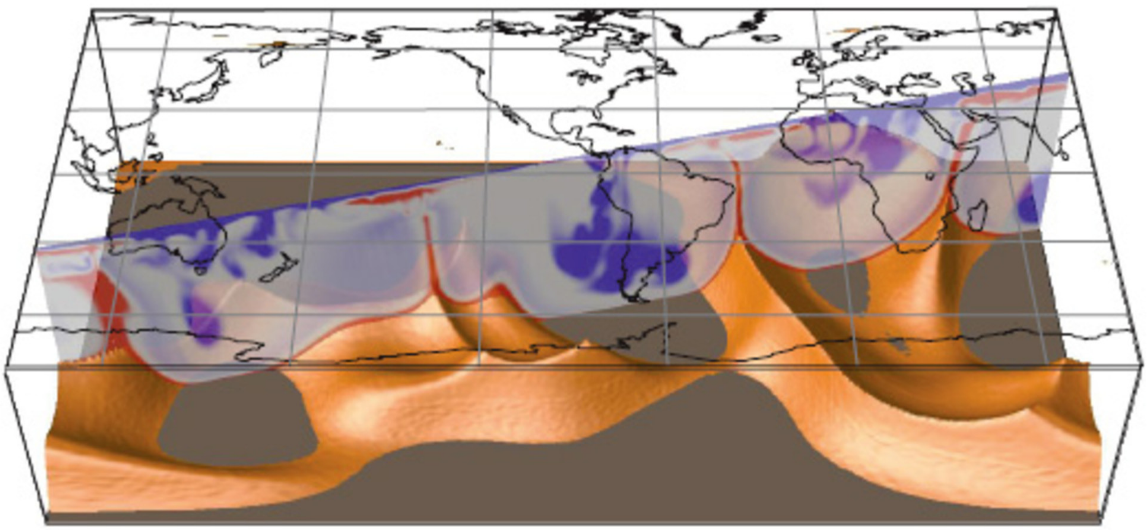

FIGURE 3.4: *Global simulation of whole mantle convection with hot cylindrical upwellings (red) and cold tabular downwellings (blue) with piles of chemically dense mantle material in the D″-layer above the core-mantle boundary, from a 3D spherical convection model. [Courtesy: A.K. McNamara]*

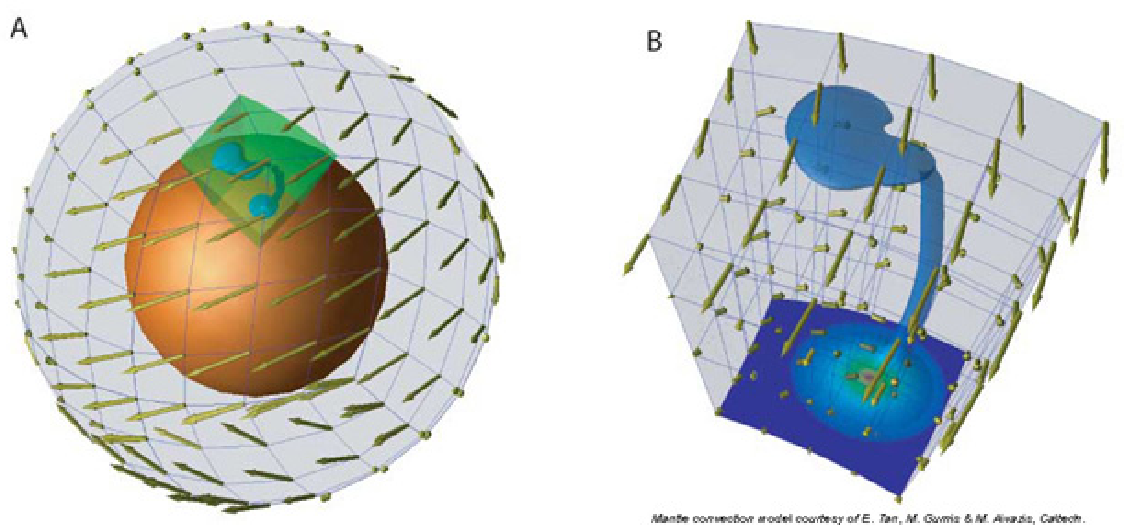

FIGURE 3.5: *Regional Simulation: Structure of a mantle thermal plume originating at the core-mantle boundary with dynamic alteration by plate tectonic scale mantle flow, from a 3D spherical convection model. A: Global view; b: cutout regional view showing plume structure. [Courtesy: E. Tan, M. Gurnis, M. Aivazis]*

Figs 3.4 and 3.5 illustrate state-of-the art 3D numerical models for some of the fundamental mantle convective processes that are important in Earth's internal evolution. These models are now able to reach realistic parameter values for each of the basic convective process involved. However, it remains very challenging to model the long time evolution of these structures at realistic parameter values. It is even more challenging to faithfully include both the larger and smaller scale dynamics within a single convection model. Future progress requires us to extend these types of calculations from short to longer, i.e., evolutionary time scales, and at the same time, incorporate dynamics over a wider range of spatial scales.

Because of these needs, it is widely anticipated that petascale computing will play an important role in evolutionary geodynamics in the coming decades. Petascale machines offer hope for exploring geodynamic phenomena over a much more extensive range of spatial and temporal scales than can be done with presently available computers. Not only will their use allow longer simulations with more realistic inputs, they can provide platforms for coupling multi-scale models together, and for assimilating large amounts of Earth data into the calculations.

Further Reading

The following is a short list of books, review papers, and topical papers on the subject discussed above.

Mantle Evolution

Schubert, G., Turcotte, D. and Olson, P., 2001. *Mantle convection in the Earth and planets*, Cambridge, Cambridge University Press.

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Nakagawa, T. and Tackley, P.J., 2004. Effects of thermo-chemical mantle convection on the thermal evolution of the Earth's core. *Earth Planet. Sci. Lett.*, 220: 107-119.

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Growth and Cycling of Continental Crust

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Stein, M. and Hoffmann, A.W., 1994. Mantle plumes and episodic crustal growth. *Nature* 372: 63-68.

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Evolution of the Core

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Nimmo, F., 2007. Thermal and compositional evolution of the core. *Treatise on Geophysics*, (Schubert, G., main ed.), v 9, Evolution of the Earth, (Stevenson, D., vol ed.), pp 217-242, Elsevier B.V.

Murthy, V.R., van Westrenen, W. and Fie, Y.W., 2003. Experimental evidence that potassium is a substantial radioactive heat source in planetary cores, *Nature* 322: 163.165.

4. Tectonics, Water, Climate, and the Biosphere

The Challenge

Water and other volatiles alter the melting point and the deformability of mantle rocks, potentially exerting important controls on mantle convection and plate tectonics. The mantle is Earth's largest reservoir, sequestering water, carbon dioxide, and other volatiles, which it exchanges with the oceans, atmosphere, cryosphere, and subsurface hydrosphere through volcanism and tectonic processes at plate boundaries. Here the grand challenges are to identify the nature and the storage capacities of deep reservoirs within the mantle and crust, determine the actual abundance of volatiles at depth, and measure rates of exchange between deep reservoirs and the exosphere. The eventual goal is to gain a planetary-scale understanding of interactions between climate, the biosphere, and geodynamic processes via the exchange of volatiles between deep reservoirs and the exosphere.

Water in the Mantle: Background

Water in the mantle is stored in hydrous minerals, as hydrous fluid phases and within the lattice structure of nominally anhydrous minerals. The presence of water reduces the creep strength of rocks, and thereby controls the nature and localization of solid and liquid deformation in the mantle. Water may play a role, for example, in the development of narrow plate boundary zones at the surface of the Earth, and it has been speculated that the absence of Earth-like plate tectonics on Venus may be due to a lack of water at its surface and in its mantle. Because variations in water content result in lateral variations in the distribution of partial-melts and viscosity, the distribution of water in the mantle plays multiple roles in mantle convection. Measuring the amount of water in the mantle and understanding its role in controlling deformation on Earth is therefore an important first step toward understanding how plate tectonics arises, and what role water may play in planetary systems that lack plate tectonics.

Water is released from the mantle into the sub-surface, atmospheric, and oceanic reservoirs via degassing of melts at mid-ocean ridges, volcanic arcs, ocean-island volcanism, and the episodic eruption of voluminous flood basalts. Water is recycled back into the mantle reservoir primarily at subduction zones. The rate of exchange of water between Earth's internal and external reservoirs is therefore intimately connected to plate tectonics and the internal convective state of the mantle. For example, it has been inferred that relatively small sea level variations through geologic time are indicative of a dynamic equilibrium between Earth's internal and external reservoirs of water; this suggests a dynamic equilibrium, involving feedbacks between the abundance of water in the mantle and at the surface, the convective state of the mantle, and plate tectonic activity.

Water in the Mantle: Milestones

The compositions of basalts that are produced by upper mantle melting at mid-ocean ridges or ocean islands indicate that the mantle source regions for these melts have widely varying amounts of water. One issue with inferring water contents of melt source regions is the effect of degassing on basalts (this problem is avoided by studying melt inclusions or least-degassed basalts, for example). Because water behaves similarly to some incompatible trace elements such as Cerium (Ce) during partial melting, water/Ce ratios are used to infer the water-content in mid-ocean ridge basalts (MORB) and ocean island basalts (OIB). These observations imply about 50-200 ppm water for the MORB source region and a much more water-rich (300-1000 ppm) source for OIB, respectively. It is worth noting that, in addition to the heterogeneity evident in upper mantle water content, these concentrations are well below the solubility inferred from low-temperature and low-pressure experiments on upper mantle minerals.

Water-rock interaction experiments that suggest that anhydrous upper mantle minerals such as olivine can store large amounts of water within their lattice structures. Experimental determinations of water storage capacity at high-pressure and high-temperature conditions appropriate to the upper mantle geotherm will be required in order to understand water solubility in the upper mantle, but the laboratory observations so far have led to two important realizations: (1) large amounts of water may be potentially sequestered in the mantle for exchange with exospheric reservoirs, and (2) the distribution of water in the mantle is probably a strong function of the depth, because of the pressure- and water fugacity-dependent storage capacity of upper mantle minerals.

Water in the Mantle: Geodynamic Interpretations

The relatively low inferred upper mantle water-content at mid-ocean ridges is consistent with the MORB source region being a depleted reservoir. One idea that has emerged is that the transition zone (410 to 660 km) may be a region of high water solubility and thus act as a reservoir of water in the upper mantle. In olivine, for example, the water storage capacity increases from 25 ppm at about 10 km to 1300 ppm at about 410 km. At higher pressures corresponding to greater depths, coexisting fluids and minerals form a melt-like mixture, so that if water is present in lattice structures, it will preferentially move to the melt/fluid. Because water storage capacity depends on pressure through water fugacity, a reduction in the water storage capacity below 660 km depth is expected. The transition zone in the mantle is therefore regarded as the most likely to have a high water storage capacity.

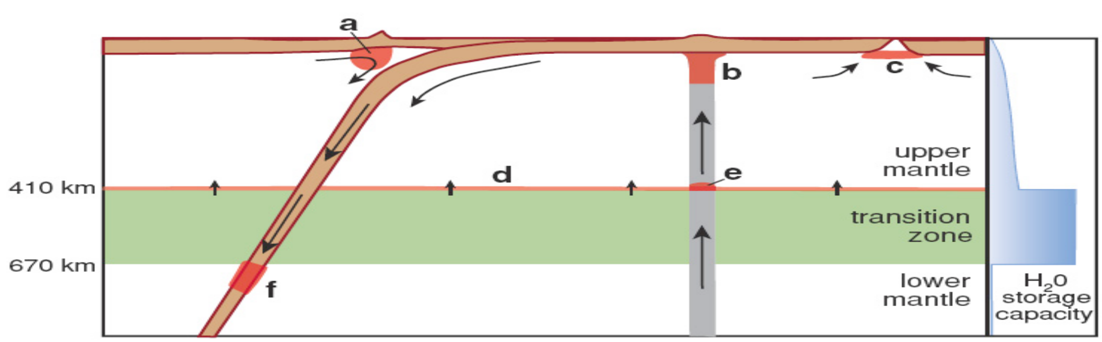

FIGURE 4: *From Hirschmann [2006]. The red shaded regions show possible regions of hydrous melting in the mantle as material moves through the transition zone, a region of anomalously high water storage capacity in the upper mantle. These include (a) melting at arcs, (b) deep regions beneath OIBs, (c) melting in the regions beneath MOR, (d) general melting above the 410 km discontinuity in response to upward motion of material through the transition zone, (e) melting within localized upwellings traveling upward across 410 km, and (f) melting as material in downwellings travels downward across the 670 km discontinuity*

The so-called “transition zone water filter” model (Fig. 4.1) demonstrates possible coupling between water and mantle dynamics. Upward material transport through the transition zone forces re-partitioning of water between mantle phases, with the possibility of accompanying partial melting. The fate of the melts produced this way is unknown, but the residual solids should in any case be less water-rich than the transition zone as a whole, providing an explanation for the relatively dry and depleted MORB source within the context of whole mantle circulation. According to this model, the lower mantle has a relatively low water storage capacity and so cannot be the water-rich source for the OIB. To account for the IOB, a wet D”-region and locally heterogeneous wet areas in the upper mantle have been proposed.

Water in the Mantle: Unresolved Issues

Major questions that relate to the water in the deep Earth and its exchange with the exosphere include:

- How much water is stored in the mantle and how does it get there? Related to this, how can we map water content in the mantle?
- How is most of the water stored in the mantle (e.g., what fraction is within nominally anhydrous minerals)?
- What are the implications of the lateral heterogeneity in upper-mantle water-content inferred from the geochemistry of MORB and OIB for mantle dynamics? How might such heterogeneous water-content be maintained over geologic time?
- How and when did water begin to be stored in the mantle? Does it originate from an early magma ocean, or was it ingested from surface water later on?
- What are ways in which water can be carried into the mantle by downgoing slabs (e.g., in which mineral phases and under what temperature and pressure conditions) and how much water do slabs introduce into the mantle?
- What are the relative fluxes of water between the mantle and the exosphere and how have these fluxes changed?
- Can the presence of H and O in the core influence the mantle water budget?

Carbon, Climate, and Geodynamics Milestones

The inorganic carbon cycle is useful for describing the exchange of carbon between Earth’s surface and its interior (Fig. 4.2). Dominant processes include the exchange of carbon between the solid Earth and the atmosphere via tectonically-controlled processes such as subduction, where volcanic degassing returns carbon (in the form of CO_2) to the atmosphere. Additionally, weathering processes, which depend on the surface relief, area exposure and exhumation of continental rocks, control the formation of carbonates in the oceans. Carbonate formation removes CO_2 from the atmosphere and tends to counteract the effects of subduction over long timescales, providing some stabilization of the atmosphere carbon content. Carbonates are in fact the largest near-surface carbon reservoir, and it has been conjectured that, without the negative feedback provided by weathering and carbonate formation, Earth's atmosphere would be subject to runaway greenhouse forcing.

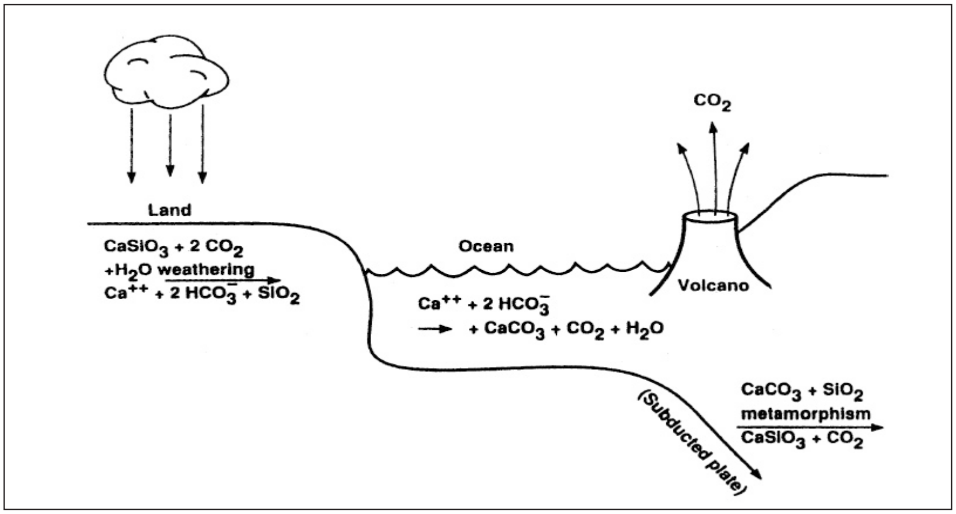

FIGURE 4.2: *From Kasting and Catling [2003]. A simplified diagram illustrating the inorganic carbon cycle. Here, silicate weathering and subsequent carbonate deposition removes carbon from the atmosphere and volcanic processes at subduction zones releases carbon to the atmosphere.*

The recognition that variability in the concentration of CO_2 in the atmosphere has played a major role in controlling climate throughout Earth history has led to a greater appreciation of Earth's mantle and crust in the global carbon cycle. These major reservoirs of carbon have limited response to short time scale CO_2 fluxes from primary production and respiration, for example, but as noted above, are very sensitive to CO_2 fluxes associated with burial of carbonates, weathering of silicate and carbonate rocks, volcanic degassing, and other geodynamical processes that operate on geologic timescales. A major piece of evidence that indicates that the feedbacks between atmospheric CO_2 and climate variability over geologic timescales is the remarkable correlation between the oxygen isotope record from shallow marine carbonates (when corrected for the effects of varying pH, this is an indicator of sea-surface temperature) and multiple, independent, proxies for the variability of atmospheric CO_2 (Fig 4.3). The carbon cycle, which determines the distribution of CO_2 and CH_4, both major greenhouse gases, can be averaged over century timescales to highlight the geodynamical processes that lead to uptake and release of CO_2 from/to the atmosphere (Fig. 4.2; simplified carbon cycle). Major geodynamic processes of CO_2 uptake include weathering of Ca- and Mg-silicates at rates that are controlled by factors such as the size, distribution, and surface relief of continents, in addition to ecological factors such as the distribution of biomass.

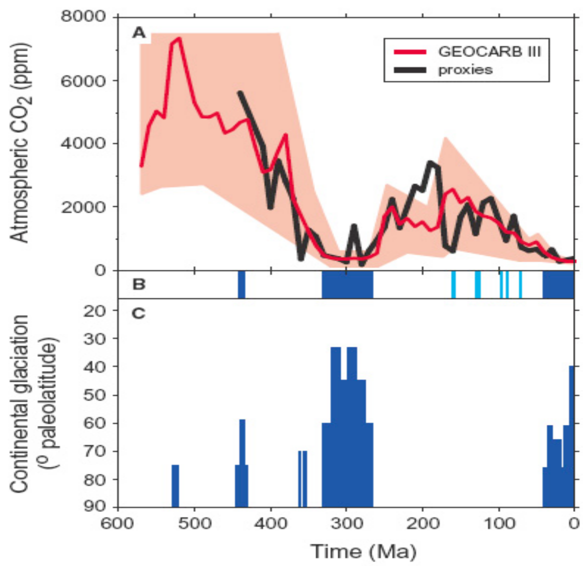

FIGURE 4.3: *Modified from Royer et al [2004]. A. An illustration of the variability in a number of CO_2 proxy data sets and the GEOCARB III model discussed by Royer et al. B. A record of glacial periods (blue shading) which correspond to cooler climates. C. Latitudinal distribution of evidence for glacial periods during the Phanerozoic.*

It is also now recognized that CO_2 release to the atmosphere by metamorphism and thermal decomposition of marine carbonates and organic matter, and the return of CO_2 to the atmosphere by volcanic emissions, are climatologically significant processes. It is important to note the stabilizing effect in this long-term part of the carbon cycle: elevated atmospheric CO_2 enhances silicate weathering rates (due to both enhanced surface temperatures and increased precipitation) causing a subsequent drawdown of atmospheric CO_2. This stabilization is occasionally disrupted by anomalous inputs of CO_2, for example, due to methane clathrate destabilization, emissions from fossil fuels, or massive biomass burning events. Stabilization may also be enhanced by biotic activity as well, i.e. warmer climates enhance cyanobacteria, azolla, flourishing of forests, etc.

We know that plate tectonics interacts in several important ways with the carbon cycle over geologic timescales. The super-continent cycle affects the latitudinal distribution, surface relief, and sizes of continents, and the total length of subduction zones, where CO_2 is returned to the atmosphere. For example, an equatorial/tropical location of super-continental land masses enhances weathering and a polar location allows for the formation of land ice (and lowering of sea level). Additionally, continental position affects oceanic circulation and oceanic transport of heat; for example, it is inferred that cooling climate during the Cenozoic since about 50 Myrs ago is related to the break up of Australia from Antarctica, setting up the polar gateway circulation that isolated Antarctica from warmer low-latitude waters and allowed permanent ice cover, which in turn strengthened the ice-albedo effect, resulting in cooling.

Recently, several new ideas have been proposed on the interactions between plate tectonics and climate. These focus on the fact that surface water allows for cooler climate and surface temperature on Earth. This make rocks at the Earth's surface more susceptible to damage and localized deformation, whereas a hotter Venus-like surface either has smaller buoyant stress in the lithosphere (because of smaller changes temperature with depth) or has higher healing rates that suppresses damage. These are discussed more fully in Chapter 2 on the generation of plate tectonics.

As these examples illustrate, global mantle convection spanning multiple super-continent cycles provides a basic time scale for long-term changes to climate system over Earth history. As well as providing a driver for climate change, it also produces global variations in rates of weathering and carbonate formation, which tend to buffer CO_2 and provide long-term stabilizing effects on the climate. It is often presumed that such geodynamic feedbacks are necessary for long-term climate stability, when considering what our own "natural state" is, and what would we need to do to restore it (including sequestration in mafic rocks), or when looking for Habitable Zones (HZ) beyond our own solar system. However, these connections between plate tectonics and climate may not be the only way to stabilize climate on planetary bodies, and other mechanisms may be possible.

Carbon, Climate, and Geodynamics Models

Geodynamic models that combine multi-phase transport, subsolidus deformation, and chemical exchange could provide important tools for exploring the long-term (Gyr) coupling between tectonics and climate. In addition to providing better understanding of past climate changes, side benefits of such models include (1) identifying other nearby modes within which our own climate system might reside, that could affect decisions on mitigation strategies, and (2) identifying new, possible Habitable Zones to help direct extra-solar planet searches.

For example, mountain building and weathering on Earth are sinks of CO_2, but perhaps on a super-Earth, basaltic volcanism might expose far more mafic material to weathering and thus remove atmospheric CO_2. On Earth, with the low viscosity of basalt flows, the resulting structures do not have enough relief to induce rapid weathering. But mafic rocks on an exoplanet might not be subject to this same limitation. The point here is that creative, process-oriented models of multi-phase deformation and chemical exchange could identify new geodynamically-based climate equilibrium configurations that might apply to past climates on Earth and also to planets beyond our solar system.

Tectonics, Climate, and Surface Evolution Milestones

Although the connection between Earth's climate and geodynamics has been the subject of a great deal of study over the past 30 years, new pieces of the picture continue to be added. We now realize that evolution of the surface, fundamentally a result of the feedback between weathering, erosion, and tectonic processes over multiple timescales, is also linked to long-term and short-term climate changes.

Heterogeneous Sea Level Rise

The non-uniform rise of sea level is an outstanding example of such complex interactions. Rapid changes in the volumes of polar ice masses are one of the anticipated consequences of global warming; indeed there is evidence that accelerated melting of the Greenland ice mass is already underway. The West Antarctic Ice Sheet is of particular concern in this regard, because of its large volume and its susceptibility to sudden collapse would entail meter-scale rises in sea level worldwide. Fig. 4.4 shows a geodynamic prediction of sea level changes following the collapse of the West Antarctic Ice Sheet. The non-uniform rise in sea level predicted for this event is a consequence of the interplay between several factors, including changes in gravity due to the redistribution of ice, water, and rock, changes in Earth's rotation, changes in the shoreline geometry, and the heterogeneous, time-dependent deformation of the mantle and crust. Note the enhanced sea-level rises around North America and in the Indian Ocean, which are nearly 30% higher than static theories predict. More generally, these calculations indicate how the melting of each polar ice leaves a distinctive pattern, i.e., a sort of "fingerprint" in the record of sea-level change.

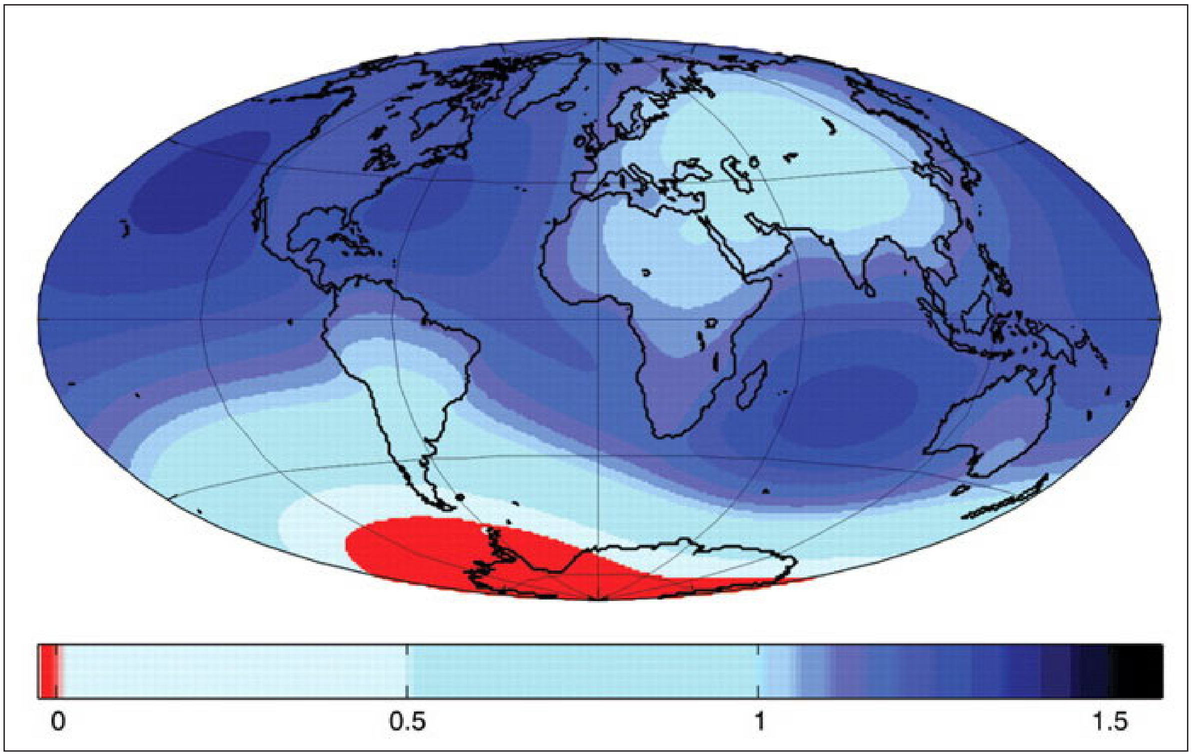

FIGURE 4.4: *Predicted sea level changes in meters following the collapse of the West Antarctic Ice Sheet, based on a theory that includes variations in ice and ocean volume, gravity, rotation, and shoreline configurations, plus deformation of the crust and mantle. From Mitrovica et al., 2009.*

The concept of an orogenic steady-state, based upon the negative feedback between topographic relief and erosion, is a useful paradigm for understanding the growth and evolution of mountain belts at convergent plate margins on longer time scales. In addition, plate reconstructions and inferred rates of past plate motions suggest that mountain-building and the topographic evolution of convergent margins may actually feedback on plate convergence rates via the frictional coupling between converging plates. On a more local scale, enhanced erosion has been inferred to control the patterns of rock uplift and exhumation so that erosion-driven tectonic responses (so-called "tectonic aneurisms") have been invoked to explain extreme exhumation patterns at certain plate margins.

Typically, landscape evolution models approach the problem by discretizing the domain of interest and integrating the effects of rock uplift (tectonics) and a range of hillslope, fluvial incision, and other surface processes. At present these models include simple feedbacks between topographic relief and erosion, e.g., diffusion-driven transport. The NSF-funded

Computational Infrastructure for Geodynamics (CIG), for example, has begun integrating simple proxies for landscape evolution processes into it a code developed for modeling of long-term tectonic deformation, GALE. Additionally, the NSF-funded Community Surface Dynamics Modeling System (CSDMS) effort attempts to extend beyond diffusion-based models and incorporate realistic fluvial and hillslope processes into landscape evolution models. These processes operate at the interface of hydrology, geomorphology, climate and tectonics, and one challenge facing the CSDMS group is to build phenomenological approaches to surface processes that can be incorporated into detailed, large-scale numerical models. The hydrologic and geomorphic processes currently included in the CSDMS are typically coupled with highly idealized tectonic forcing. One way in which geodynamicists can contribute to understanding the interplay between surface processes, climate, and tectonics is to work with groups like CSDMS to build more sophisticated tectonic evolution into a realistic surface process model and therefore address long time scale interactions.

Geodynamic Interactions with the Biosphere

Historically, the study of geodynamic effects on the biosphere have emphasized the role of plate tectonics in re-configuring the distribution of ocean basins and continents. Recently however, attention has been given to more catastrophic processes such as sudden methane release and large-scale volcanism. The important point here is that these diverse processes are linked dynamically; the challenge is to understand their linkage, rather than how they may or may not affect the biosphere in isolation. Possible interactions between geodynamics and the biosphere include:

1. The rise of cyanobacteria and O_2 reduced atmosphere CO_2 , possibly contributing to early Snowball-Earth events at times when the continent-ocean configuration favored large climatic extremes.
2. Massive flood basalt eruptions are known to be co-incident with major Phanerozoic mass depletion events, suggesting a possible causal relationship between these eruptions and global toxicity or short climate events.
3. The well-documented Paleocene-Eocene Thermal Maximum (PETM) climate event, possibly caused by release of CH_4 from deep sea clathrates by hydrothermal activity linked to sea floor spreading.

Requirements for Progress

Advanced modeling capabilities will be needed to meaningfully address the geodynamics of global environmental change. To accomplish this, we need to augment current geodynamical models of lithosphere and mantle deformation, by adding realistic volatile storage and transport, multiple phases, chemical reactions, and exchange with the hydrosphere, atmosphere and biosphere. Since these processes typically operate over highly disparate ranges of time and spatial scales, successful models of this type necessarily will entail multiple scale approaches, parameterizations, and novel coupling schemes.

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Water in the Mantle

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5. Dynamics of the Continents: Interiors, Roots, and Margins

The Challenge

The success of plate tectonics in explaining the motion of large blocks of rigid lithosphere delineated by narrow boundary zones where deformation is concentrated was a major revolution in geophysics. Plate tectonics often breaks down on the continents, however, where deformation, faulting, and earthquakes occur thousands of kilometers from plate boundaries. How the continents, including their deep roots, nearly rigid interiors, and deforming margins accommodate tectonic plate motions is a future grand challenge for geodynamics.

Milestone Accomplishments

Significant leaps forward in our understanding of the dynamics of continental plate boundaries followed the deployment of large Global Positioning System (GPS) networks. These networks vastly improved the resolution of diffuse deformation in tectonically active continental regions. Surprisingly, several such regions long thought to be rigid are now known to have measurable deformation, corresponding to relative surface motions of several millimeters per year. These GPS experiments are redefining what a "stable" plate means, and are providing constraints on the forces that drive continental deformation.

We have also learned that, in some continental regions, buoyancy forces associated with topography and crustal thickness variations along with boundary forces, can account for the majority of their large-scale deformation. Additionally, the identification of regions of seismic anisotropy caused by the preferred alignment of minerals within the Earth's lower crust and upper mantle has provided a complementary set of observations to the GPS data. By combining the observed anisotropy observations with laboratory data, we have begun to deduce the orientation of shear at depth. This new information allows us to infer the mantle flow beneath cratons and deforming continental lithosphere, as well as the flow within the lower crust, and has led to new geodynamic interpretations of these processes, on regional and global scales.

Unresolved Questions

Despite the advances in observations and new geodynamic interpretations, many fundamental unresolved questions related to continental dynamics remain, including:

1. What is the exact nature of deforming continental lithosphere?
2. What controls the rheological properties of continents?
3. How do cratons remain thick and undeformed over hundreds of millions of years?
4. What is the role of basal tractions produced by large-scale mantle flow in driving continental deformation?
5. What effect does the delamination of thickened lithosphere have on the surface deformation pattern?
6. How is strength within the continental lithosphere distributed with depth?
7. What is the role of lower crustal flow in driving surface deformation?

8. What drives intra-plate continental deformation?
9. What does seismic anisotropy represent in the crust and mantle?
10. What is the role of dynamic topography in continental dynamics?

Background

The Earth's lithosphere, consisting of the crust and uppermost mantle, comprises the rigid tectonic plates, in which deformation is accommodated through earthquakes and faulting within narrow boundary zones. In the lithosphere, heat is transported primarily by conduction. The asthenosphere, the portion of the mantle directly below the lithosphere, is mechanically weaker on geological time scales, deforms by subsolidus flow mechanisms, with heat transported primarily by subsolidus convection. As described above, continental regions remain anomalous in plate tectonic theory, because unlike their oceanic counterparts, deformation is not limited to narrow boundary zones. Continental lithosphere also involves large surface topography, very complex deformational styles, and widely varying intrinsic strength. Prime examples of deformed continental zones include the India-Eurasia collision zone, the western North American plate boundary zone, the Andes and Aegean regions. Continental lithosphere thicknesses are also highly variable from region to region. For example, lithosphere under the western United States has been estimated to be as thin as 30 km, where it has been hypothesized that portions of the lithosphere are currently detaching or have detached in the past. In contrast, some cratonic regions are estimated to be as thick as 250 km and have withstood erosion by the convecting mantle for billions of years.

Recent Progress

Because of the diffuse and complex nature of continental plate boundary zones, classical methods such as those obtained from sea floor spreading rates do not adequately describe their heterogeneous deformation. Methods for quantifying how relative plate motions are accommodated across these broad zones can be grouped into two end member approaches: 1) block models, where all relative motions are accommodated along faults between rigid blocks in a mini-plate tectonics system, and 2) continuous models, where relative plate motions are accommodated within the entire model region and the effect of individual faults are integrated over kilometer length-scales. Both types of models use seismicity, known faults and their slip rates, and GPS observations to quantify the surface deformation field. Although there has been a significant improvement in kinematic constraints, multiple types of kinematic models are able to fit the data equally well. In Tibet for example, several block models with different block geometries fit the GPS data within the uncertainty as well as the continuous models do.

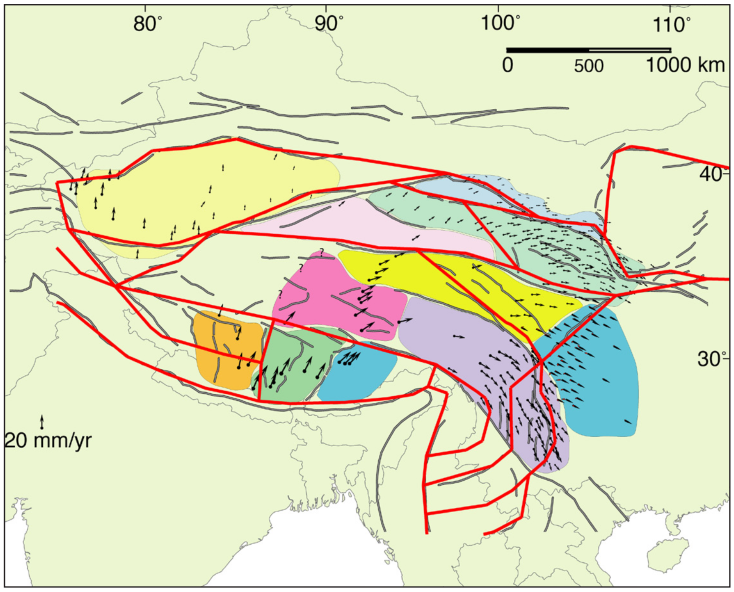

FIGURE 5.1: *A dense network of GPS observations from Zhang et al. (2004) (black vectors) quantify how deformation between India and Eurasia is accommodated. Superposition of Tibetan block boundaries from Meade (2007) (red lines) and block boundaries from Thatcher (2006) (colored polygons) shows differences in these boundaries between two kinematic models that both fit existing GPS data. The largest differences occur in areas with the most data. (From Flesch and Bendick, 2007.)*

This non-uniqueness may result from assumptions related to the permanent deformation signal in the GPS data, or could indicate a fundamental lack of understanding of the exact nature of the deforming continental lithosphere. Despite the differences in the kinematic modeling techniques, these results have provided a first order deformational constraint with which to assess the forces driving continental deformation.

A significant amount of research in continental dynamics has focused on continental plate boundaries at length scales that vary from regional to plate scale. As with the kinematic models, continental lithosphere has been modeled dynamically by treating the lithosphere as rigid blocks or a viscous continuum. Block dynamic models (both analog and numerical) that feature stepwise growth of mountain ranges are able to explain many geologic surface features but are unable to account for lithosphere thickening. Continuous thin viscous sheet models assume that the lateral length-scale of the deforming region is significantly larger than the thickness of the lithosphere, allowing the physical parameters to be integrated over the lithospheric thickness. These models have been successful at reproducing many first order topographic features in continental settings, and have identified the relative importance of gravitational collapse of topography (buoyancy forces), the integrated effects of tractions up to the model boundary (boundary forces) and tractions applied at the base of the lithosphere resulting from flow within the mantle.

Thin viscous sheet models also allow for the quantification of vertically integrated stresses acting throughout the lithosphere, and combining these with kinematic observations provides information on the vertically integrated effective viscosity of continental lithosphere. Estimation of the effective crustal viscosity can also be made by relating heat flow to earthquake activity. These diverse approaches indicate there are large viscosity variations (over two order of magnitudes) within continental lithosphere. However, what controls these lateral strength variations, and how that strength is partitioned with depth, remain actively-debated topics.

Using strength parameterizations derived from rock mechanic experiments, continental lithosphere deformation has also been modeled in 2-D cross section and also in 3-D. Usually these models assume a sandwich-type rheology, with strong upper crust, weaker flowing lower crust, and stronger upper mantle. By resolving the cross-sectional dynamics, these approaches focus on the role of vertical strength variations in influencing of mountain building and plateau growth processes. For example, these models applied to the Tibetan plateau are able to generate the observed topography and reproduce first-order features in the surface deformation, however, their crustal thickness predictions are inconsistent with seismic observations. Some geodynamicists argue that only by incorporating of a very weak lower crust channel, which is redistributed from the interior of the thickened plateau inflating the margins, will produce the observed topographic gradients be produced, and indeed recent seismic observations show patches of low seismic velocity in the lower crust that possibly correspond to this weaker material.

There is a general consensus that, in deforming continental plate boundary zones, equal contributions of buoyancy forces and boundary forces account for the first order features of the observed deformation. Less well-known is how tractions are applied to the base of the lithosphere, from either local or global-scale convection cells. Large-scale global models that incorporate mantle density heterogeneities to drive convective flow have been used to predict tractions applied at the base of the lithosphere. In these models, variations in density that induce mantle flow are inferred from seismic wave speed anomalies and the history of past subduction. In general, these flow models tend to have a uniform thickness lithosphere and assume a radially varying viscosity structure. The tractions at the base of the lithosphere calculated this way are then applied to the thin sheet lithosphere models, to calculate the internal lithosphere stress distribution. In this approach, the magnitude and direction of the basal tractions and resulting stress field are sensitive to the assumed mantle viscosity structure. Estimates of lithosphere stress magnitudes associated with basal tractions currently span two orders of magnitudes. Incorporation of lateral variations in the viscosity structure further influence the basal tractions and internal lithosphere stress.

Buoyancy-driven instabilities are another source of continental deformation. The convergence of two tectonic plates can result in the development of mountain belts and high plateaus, as well as a crustal root beneath supporting this topography. This thickened cooler and denser root can become unstable and sink into the mantle, generating secondary motions that contribute additional surface deformation.

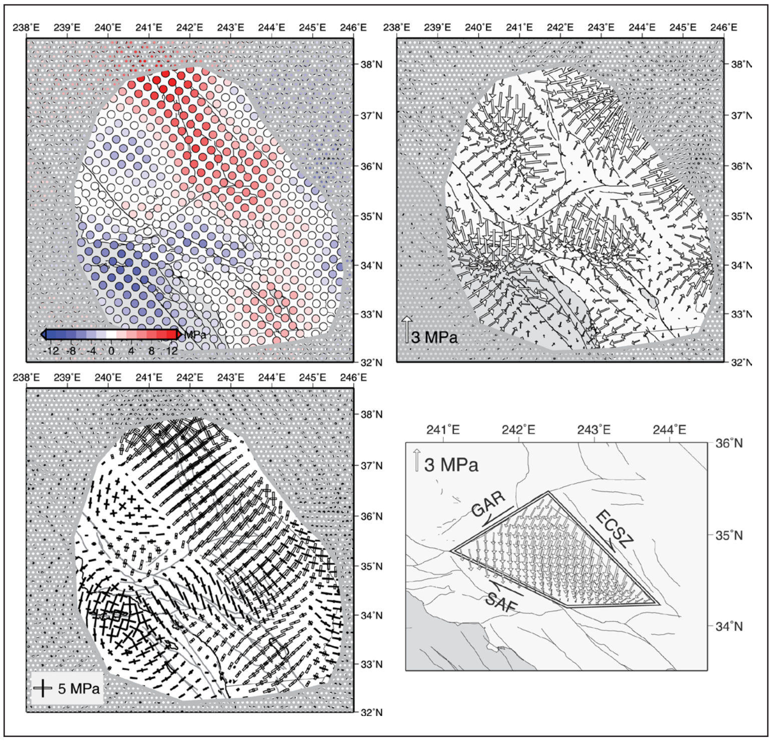

FIGURE 5.2: *Small-scale convection in the upper mantle. Density variations within the mantle drive convective flow. This occurs on a global scale and generates plate motions, as well as on a regional scale where local density variations in the upper mantle drive small-scale convection cells that influence regional crustal motions. Estimates of mantle density in southern California are inferred from shear wave density structure (Yang and Forthsyth, 2006) where low seismic velocities beneath volcanic regions are interpreted to be zone of mantle upwelling. Fay et al. (2008) used this density structure to determine the small-scale convection patterns using a 3-D viscous flow model and calculate the resulting normal tractions (upper left) and shear tractions (uppper right) at the base of the crust. These tractions are then used to calculate the resulting stresses applied within the crust (lower left). A comparsion of these results with observations from GPS suggests that these tractions provide a significnt contribution to the surface deformaton. A balancing of forces on the Mojave block (lower right) aruges that shorting in the transverse ranges and bend in the San Andreas fault may be due to the small-scale convection cell appling counter clockwise tractions at the base of the block, not a result of the bend itself. (adapted from Fay et al., 2008.)*

The longevity of cratons to resist deformation and erosion from the flowing mantle below, relative unstable and delaminating thickened lithosphere, has been modeled both chemically and thermally, with explanations to account for their long-term stability relating to heat production within the mantle, chemical formation of the thickened region, intrinsic chemical buoyancy, and to the speed of mantle flow around the craton. Seismic evidence indicates different chemical signatures associated with cratons relative to other lithosphere regions.

New Observations, New Modeling Approaches

In the past 15-25 years there has been a significant increase in the number of high quality geophysical data that has begun to illuminate ongoing processes occurring within and below continents. For example, observations of deformation occurring within "stable" plate regions, rapid variations in seismic wave speeds revealing detailed structure within the crust and mantle, identification of the lithosphere asthenosphere boundary, and rapidly varying topography of the Moho and lithosphere asthenosphere boundary. The integration of this data into geodynamic models has been driving the recent progress and rewriting paradigms in continental dynamics. A prime example is data and resulting models from the Earthscope initiative. The unprecedented geodetic and seismic deployments have allowed for detailed images of seismic velocity structures beneath the western United States. High velocity regions, inferred to represent colder denser material, beneath the northern Sierra Nevada mountains have been interpreted to be a thickened crustal root. Slower velocity structures, inferred to be warmer buoyant material, as well as a gap in the crust/mantle boundary are imaged beneath the southern Sierra Nevada. These observations combined with past volcanism and surface subsidence provide significant evidence for ongoing asymmetric delamination of a crustal root. This has motivated updating models of instability to understand the factors that lead to asymmetric removal. The tractions and stresses acting on the base of the crust in southern California associated with this local convection cell have been modeled in conjunction with surface deformation data to quantify forces acting on individual crustal blocks in the region. GPS velocities from the Earthscope project have measured surface motions within the continental interior at stations east of the Rio Grande Rift within the "stable" plate. Geodynamic models of the region argue for both an active and passive source of rifting. Furthermore, the highly variable crustal thickness observations require reassessment of the modes of compensation, especially in regions where the topography of the Moho is more highly variable than surface topography.

The quantification of the broad deformation occurring in the western United States has been used in conjunction with deviatoric stress estimates from lithospheric gravitational potential energy variations to calibrate the levels of basal tractions applied from global mantle flow. The calibration of basal tractions in turn yields allowable viscosity contrasts between the lithosphere and asthenosphere beneath the western United States. However, a thicker continental lithosphere in North America within cratonic region will produce a larger drag from basal tractions thus resulting in larger tractions. Global mantle flow models are now beginning to incorporate these laterally varying viscosity structures, to investigate the dependency of basal tractions and resulting lithospheric stresses on lithospheric thickness.

The incorporation of seismic anisotropy data into geodynamic models on both a global and regional scale has yielded additional information on the role of mantle in driving continental dynamics. Large-scale global convection models, surface plate motions and the direction of seismic anisotropy provide constraints on relative strength variations at the base of the lithosphere between oceans and continents. The surface velocity field and direction of seismic anisotropy constrains the flow beneath deforming continental lithosphere and provides information on plate motions relative to the deep mantle reference frame.

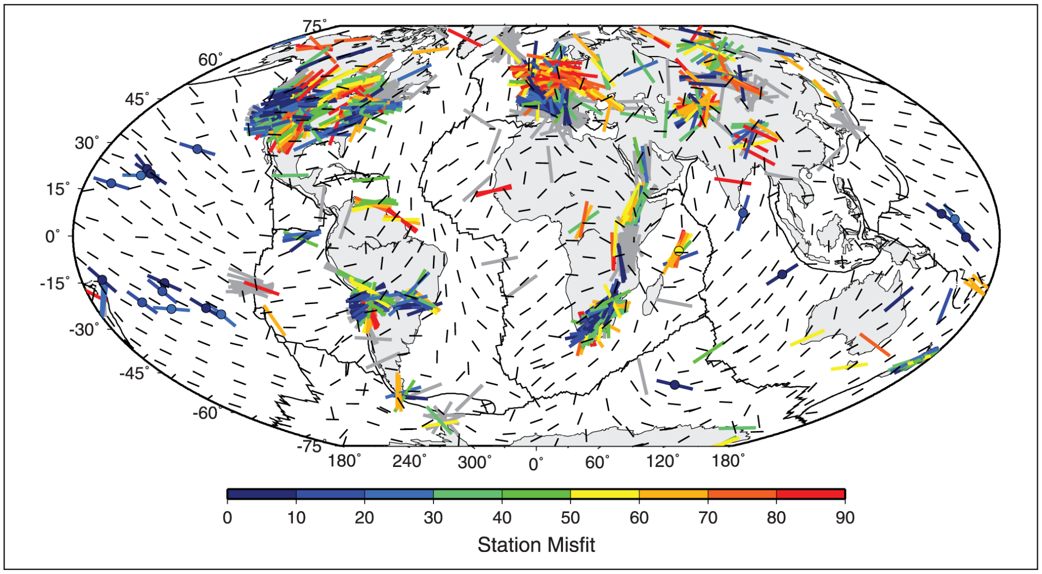

FIGURE 5.3: *The predicted fast axis anisotropy direction determined from the flow generated from the differential velocity of global plate motions and large-scale mantle flow (black bars) at 225 km depth, and the observed anisotropy directions (colored bars). (From Conrad et al., 2007.)*

The Future

Keys to progress in continental dynamics involve determining the strength, thickness, and compositional variations of continental lithosphere. This task will ultimately be accomplished by isolating the factors that control variations in continental strength across terrain boundaries. It is important to identify these properties over a wide range of spatial and temporal scales. With the current acquisition of high quality geologic, geodetic and seismic data, continental structure and surface motions are known at unprecedented levels. However, even within a single region, analysis and interpretation of this data has led to very different conclusions about seismic structure and deformational styles, so that even better observational control is needed

Geodynamic models of the continents should be data driven and test the hypothesis put forth by these new observations. This will involve integrating results from both short-term and long-term models, for example, coupling flow from small-scale convection with both long-term flow associated with global mantle convection and long-term deformation at the surface. This task requires better understanding of transient and long-term signals contained within the surface deformation field. Models need to further test the assumption that slow seismic velocities represent hot material and fast seismic velocities cold material to understand the role that both temperature and compositional variations play in the determination of seismic wave speeds. These observations should be used in conjunction with earthquakes, geologic data, and history of volcanism to understand the role played by previous tectonic events in driving present day deformation. This requires understanding not just effective rheologies but a need to understand multi-phase systems and coupling time dependant chemistry into models of continental evolution. Knowledge of the compositional variations will elucidate the role density variations within the mantle in supporting topography. Continued quantification of the role that the deeper mantle plays in driving surface motions at and away from continental plate boundaries will need to account for lateral thickness and strength variations within the model lithospheric shell, as well as lateral variations in the assumed viscosity structure of the asthenosphere. These endeavors require further progress on modeling the origin of anisotropy in the lower crust and upper mantle.

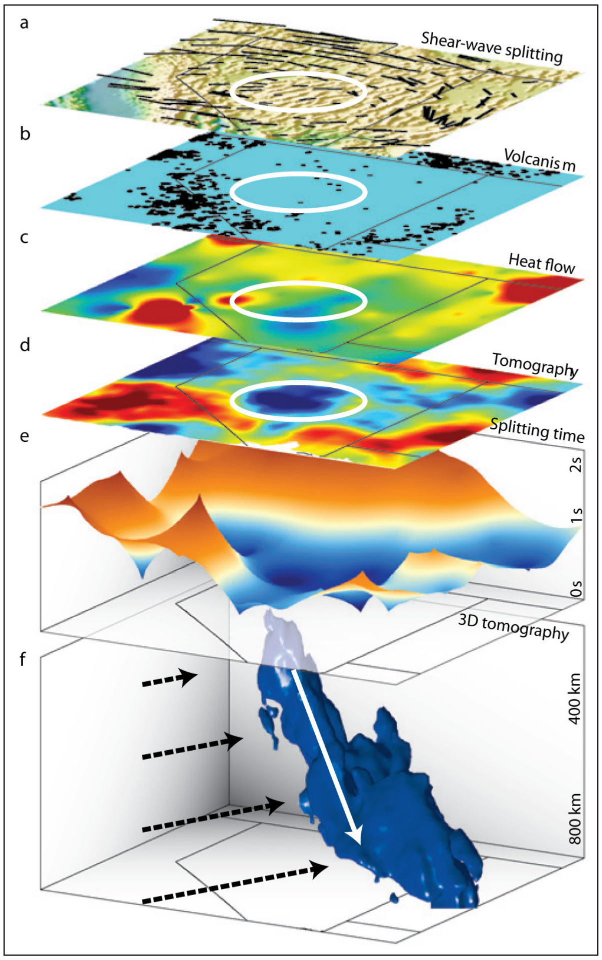

FIGURE 5.4: *Data driven hypothesis testing with geodynamic models. The proliferation of high quality geophysical data has generated new and sometimes unexpected hypothesis about processes occurring within continents. An example of this is new seismic models determined using data from the EarthScope initiative. West et al. (2009) have combined 3-D seismic tomography, anisotropy, heat flow, and volcanism data to argue that a large section of the lithosphere here has detached and sinking into the asthenosphere towards the center of the earth. Other tomography models predict that this seismic velocity anomaly is either in a different region or simply not present. A sinking lithospheric blob will have direct implications on the deformation observed at the surface and testable hypothesis of processes occurring beneath Nevada. Geodynamic modeling of a seismically fast region with a direct comparison of results to surface observations will allow for a better understanding of what this seismically fast region of the mantle represents.*

Continued exploration is required to understand the exact nature of deforming continental lithosphere. By understanding the factors that control strength variations in the continental lithosphere we may begin to know what is responsible for keeping cratons strong and continental boundaries relatively weak. It is also necessary to understand the role that vertical strength variations play in the evolution of mountain belts and coupling stress through continental lithosphere. In order to fully understand forces driving continental deformation, the role of tractions applied at the base of the crust and lithosphere need to be quantified to assess the integrated effect of small-scale convection cells and global mantle flow on surface deformation.

Community Structures

In order to meet the goals laid out above, we need to move beyond traditional end member models and simple geodynamic paradigms. We need data-driven models that link processes occurring on all scales, both spatial and temporal, that are comprehensive enough for real hypothesis testing. As has been emphasized by CIG (Computational Infrastructure for Geodynamics), standardizing input and output of benchmarked geodynamic models is important, so that independent users can compare results, and interdisciplinary groups can address the challenges listed above.

Further Reading

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6. Intra-plate Volcanism

The Challenge

Plate tectonics provides the unified conceptual framework for explaining volcanism at mid-ocean ridge and island arc settings, however, the origins of intra-plate volcanism remain controversial, particularly for major long-lived, mid-plate hotspots such as Hawaii. Here the challenges are to understand the nature of the mantle flow and the compositional and thermal anomalies that produce this intra-plate melting, and to identify their ultimate source regions in the Earth's interior.

Milestone Developments

The original mantle plume hypothesis—localized, hot upwellings from the deep mantle that produce nearly stationary, long-lived melting spots—offers a dynamically straightforward explanation for much of intra-plate volcanism, in the form of decompression melting of mantle rock at sub-lithosphere depths during ascent in a plume conduit. Although the plume concept is supported by diverse lines of evidence, the existence of plume structures in the lower mantle has never been conclusively demonstrated, and there remain some aspects of intra-plate volcanism and uplift that are not readily explained by the plume theory.

This situation has led some to question the applicability of the mantle plume theory to intra-plate volcanism, and a lively debate on this issue has ensued, well-described in several recent GSA Special Publications. Some of the main drivers for the present controversy involve shortcomings in plume-related explanations for the observed patterns of volcanism and uplift around major hotspots. To plume proponents, these shortcomings are simply details that will eventually be worked out. To critics however, they represent genuine failings that cannot be readily dismissed 35 years after the plume model was proposed, and they signify that a new geodynamic theory for intra-plate volcanism is needed.

In order to resolve this controversy, there is urgent need better seismic imaging of the mantle beneath hotspots, and there is an equally urgent need for geodynamic models that can distinguish between the plume or other melting sources in terms of mantle flow, melting pattern, melt migration, and melt chemistry, both in oceanic and continental lithosphere settings.

Fundamental Questions

Controversy over the source of intra-plate volcanism is rooted in a number of fundamental, unanswered geodynamic questions, including:

- What are the flow, compositional, and thermal anomalies linked to intra-plate melting?
- By what processes do these melts rise through the mantle and crust?
- How important are the chemical transformations that occur in a melt migrating between the site of melting and the near surface?
- What are the significant interactions between migrating melt and the deforming mantle?

Questions more specifically related to the plume theory include:

- How much intra-plate volcanism is plume-related?
- How do changes in the thickness of the lithosphere affect mantle plume volcanism?
- Is hotspot magmatism caused by direct mantle upwelling, or is it caused by a secondary convective instability?
- Is there a plume contribution to the asthenosphere? If so, how does it influence global tectonics?

Each of these geodynamic questions demands better quantitative modeling of plume-lithosphere interactions, including shallow mantle flow and melting. More accurate and more complete quantitative models can sharpen observational tests, explore for possible links between apparently unrelated phenomena, and test the viability of various 'cartoon' (i.e., qualitative and generally over-simplified) models that tend to dominate the discussion. Here we focus on how to test current hypotheses for mantle-flow-linked origins to intra-plate volcanism, and then discuss the additional developments needed for the more general problems of mantle melt-migration and melt-rock interactions.

Background

There are several simple reasons why plume-lithosphere interaction remains a frontier problem. It involves the intersection of two poorly-quantified parts of geodynamics: (1) dynamics near the 'base' of the lithosphere, and (2) the effects of melting and melt migration on magma composition and rock rheology. We need to better understand the rheological changes that define the 'base' of the lithosphere and the lithosphere-asthenosphere transition. Rheology is a parameter that is very sensitive to temperature, compositional impurities, and the past history of strain. In addition, modeling the flow with strongly-variable viscosity remains difficult computational, particularly in three dimensions. Study of the lithosphere-asthenosphere transition is an active area of interdisciplinary research in mineral physics, seismological and other geophysical imaging, and geodynamics. We also need to better understand and be able to model mantle flow, melting, and melt migration and possible melt-rock reactions with ascending magmas. These issues, while central to much of the standard interpretations in petrology and geochemistry, have been the subject of relatively little direct quantitative research due to their complexity. However, once we have a better capability to accurately characterize and model plume-lithosphere interaction, then we will also better understand plate boundaries, and better incorporate the lithosphere-asthenosphere transition in theories and experiments that explore island arc, ridge, and rift volcanism. The base of the lithosphere has always been vaguely quantified, as this is the region of transition between a plate-like to an asthenosphere-like rheology. In addition to the well-accepted thermal lithosphere, there is a 'compositional lithosphere' created by the dehydration-linked increase in viscosity due to partial melt-extraction. Lab experiments have shown that if partial melting removes the small amount of water (~200 ppm) generally thought to exist within mantle peridotite, then the viscosity increases 100-fold or more. Thus the rheology of this region may even involve interactions between ridge melt-extraction-related and plume melt-extraction-related processes.

Example Focus Areas

A. Origins of Hawaiian Arch Volcanism: possible links between arch volcanism, on-chain volcanism, and Hawaiian swell relief

The Hawaiian seamount chain is the type example for the development of a hotspot swell on a plate migrating with respect to an underlying mantle plume. At Hawaii, a ~150-200 km wide island chain lies within a ~1 km high, ~800-1000 km broad bathymetric swell (Figure 6.1a).

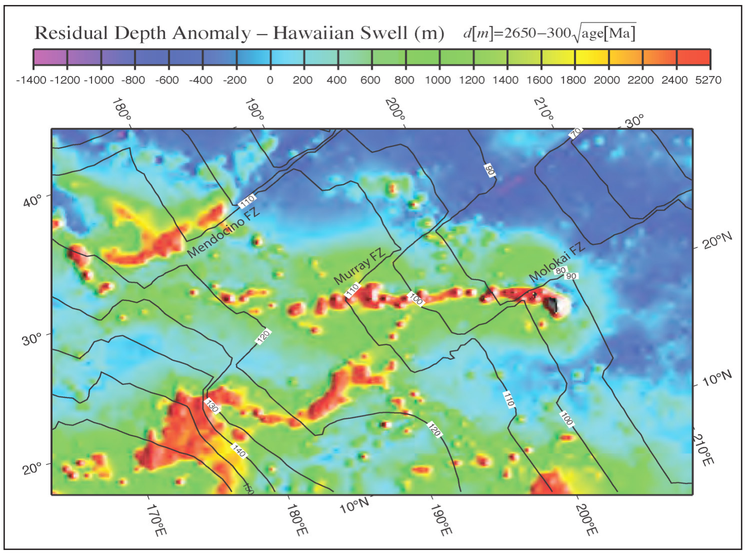

FIGURE 6.1A: *Bathymetry around the Hawaiian Island Chain corrected for the effects of seafloor depth vs. age. The Hawaiian swell is a pronounced bathymetry feature rising ~1200m above the surrounding seafloor. Seafloor ages are shown by the contour lines in Ma.*

The presence of this swell is in fact one of the strongest pieces of evidence for a plume-related origin for Hawaiian volcanism, as no existing non-plume hypothesis has been able to explain why a broad regional swell should be linked to Hawaiian volcanism. Furthermore, extensive seafloor mapping surveys and sampling studies within the US Exclusive Economic Zone (EEZ) have shown that, in addition to the well known age-progression from main-stage to late-stage volcanism that is found along the subareal island-chain, there is geologically recent off-island volcanism—so-called 'arch-volcanism' (Figure 6.1c). The lithospheric thickness offset across the obliquely striking Molokai Fracture zone appears to be linked to both the presence of arch volcanism on the younger-age side of this fracture zone, and is also correlated with more swell relief on the young side of the fracture zone.

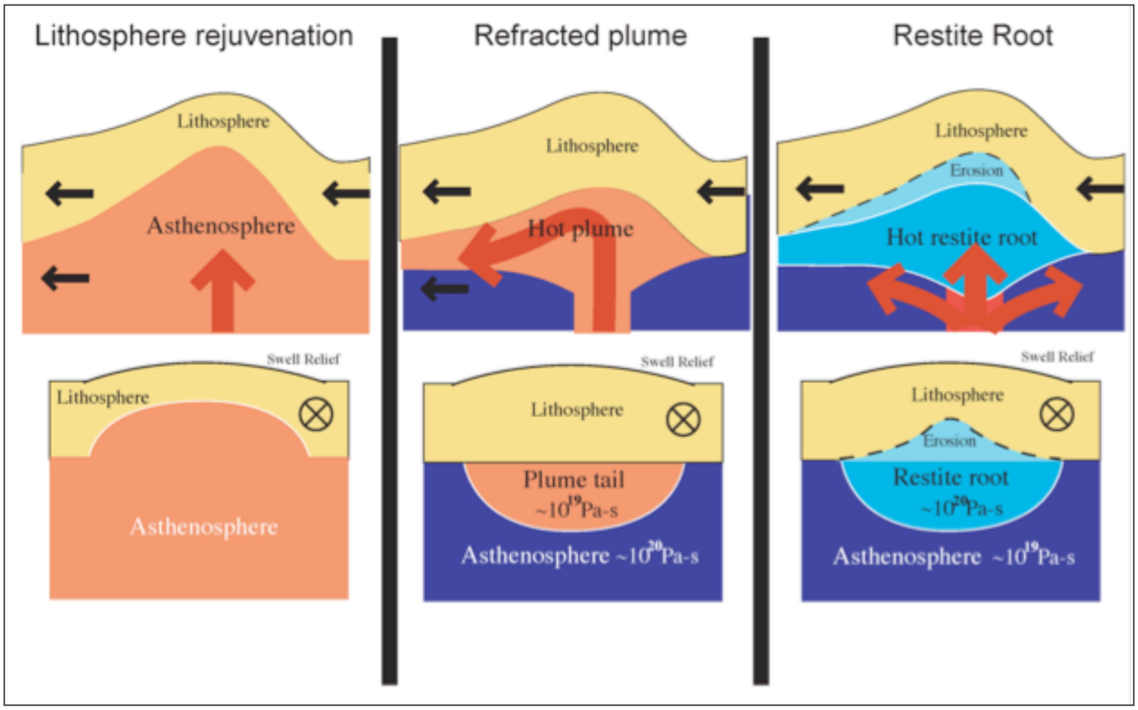

FIGURE 6.1B: *Cartoons of three popular scenarios for the uplift of a hotspot swell; Lithosphere rejuvenation (left), a refracted plume (middle), and a restite-root (right). For each scenario a schematic cross-section is shown along the island-chain (top) and perpendicular to the island-chain (bottom). The key conceptual difference between the refracted plume and restite-root hypotheses is that the refracted plume is the entire flux of low viscosity plume material that is bent and dragged by the overriding lithosphere and underlying higher-viscosity asthenosphere, while the restite-root is the hot, more viscous restite residue to hotspot melt-extraction that is created when partial melt-extraction dries and thereby strengthens the restite so that it is hotter, yet more viscous than underlying cooler but wetter asthenosphere. In the restite-root scenario only the hottest core of an upwelling plume is likely to undergo enough partial melt-extraction to become more viscous restite, the cooler rim of upwelling plume material becomes asthenosphere.*

The initial hypothesis for hotspot swells was the 'lithosphere rejuvenation' model shown in Figure 6.1b, in which the lowermost ~50 km of the lithosphere is removed during passage over a mantle plume, with the largest lithosphere removal beneath the island chain, and partial removal extending up to 500 km to the front and sides of the island chain. This theory explains the topography and gravity anomalies associated with the swell with a simple—albeit mechanically vague—conceptual model. However, the excess heat flow predicted by this hypothesis was not found in the experiments designed to test it. The attempt to explain the 'missing' heat flow as a byproduct of hydrothermal flow was also unsuccessful. Recent seismic evidence that the onset of significant lithosphere erosion occurs well downstream from initial swell uplift is a further strong argument against this hypothesis in its pure form, since the lithosphere rejuvenation model predicts that the region of lithosphere erosion should directly underlie the region with swell relief, yet recent observations imply that it does not.

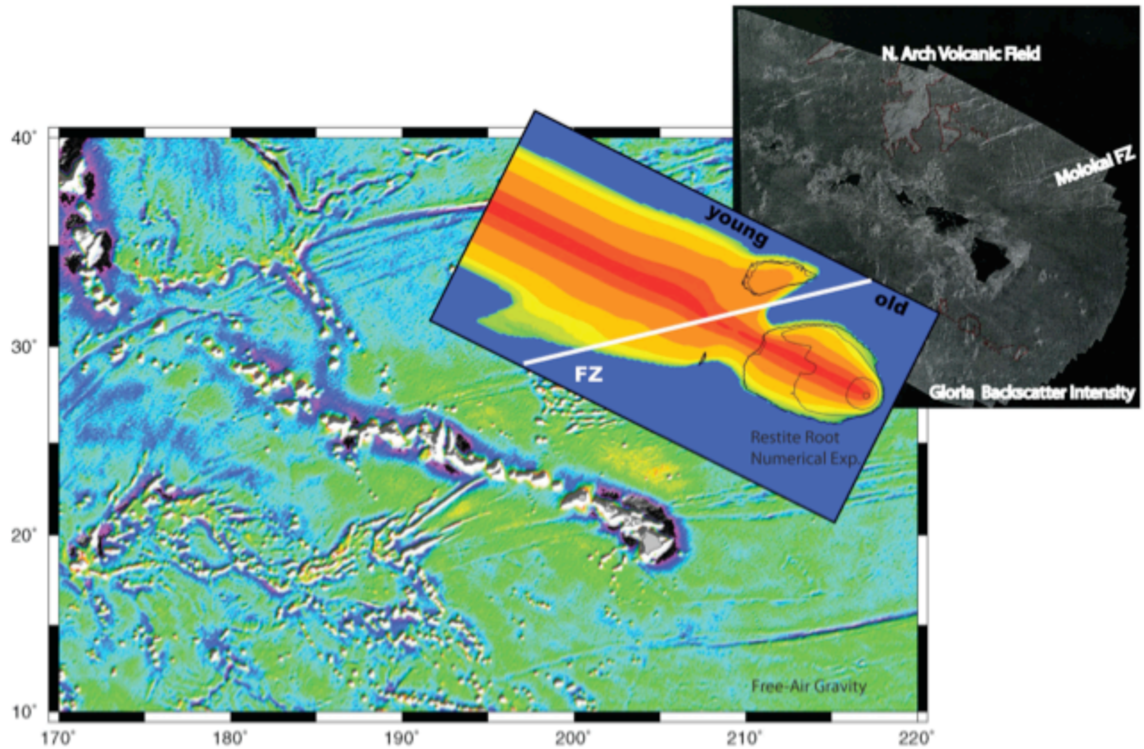

FIGURE 6.1C: *Regional free-air gravity and off-chain distribution of arch volcanism around the Hawaiian Island Chain. Seafloor backscatter intensity from Gloria Side-scan mapping of the Hawaiian Exclusive Economic Zone shows fields of Arch volcanism (upper-right panel) that are sketched in the lower-right panel. For comparison, the pattern of current off-chain volcanism predicted by the restite-root hypothesis is shown in the central panel. Logarithmic contour lines show regions of predicted current melt generation while colors show the predicted crustal thickness variations. Figure 6.2a has a more-detailed description of this panel. From Yamamoto and Phipps Morgan (2009).*

Subsequent work has focused on two variants of the idea that buoyant material associated with the plume may be the origin of regional hotspot swell uplift. Figure 6.1b shows the basic conceptual difference between the two ideas. In the 'refracted plume' hypothesis, the hot and low-viscosity plume is bent ('refracted') and dragged by the shear of the moving plate as it laterally spreads into cooler and higher viscosity ambient asthenosphere. In the 'restite-root' hypothesis, partial melt-extraction from the central region of the upwelling plume induces a desiccation-linked increase in the viscosity of this hot buoyant material. For this scenario, the swell-root consists of material of a viscosity of ~3x1020 Pa-s, i.e. ~10-100 times more viscous than ambient wetter and cooler surrounding asthenosphere. (This viscosity for the Hawaiian swell-root was inferred from the observed rate of its lateral spreading.)

Numerical experiments have suggested that the refracted plume and restite-root hypotheses predict similar melting patterns and swell relief for a plume upwelling beneath constant-thickness lithosphere. However, when a plume migrates beneath a fracture zone offsetting lithosphere of different age/thickness, then significant differences are anticipated between the predictions of the restite-root and refracted plume scenarios for the time-evolution and spatial distribution of sublithospheric melt production. Here we illustrate a scenario whose geometry is like that during the recent (~2.7 Ma) passage of the obliquely-striking Molokai Fracture Zone (FZ) above the Hawaiian plume, in which the plume-stem migrated beneath older and thicker lithosphere.

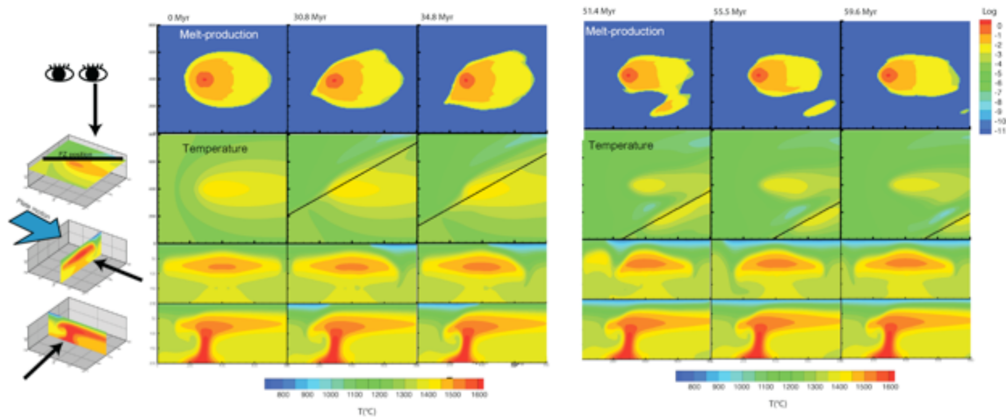

FIGURE 6.2A: *Snapshots showing the time-evolution of the restite-root experiment for migration of an oblique fracture zone with a change in lithosphere thickness from 90km to 100km—i.e. snapshots corresponding to the time-integrated history shown in the top-right panel of Figure 1c. Vertical sum of underlying melt production is shown in the top panels; lower panels show time-variation of the temperature field in the slices illustrated at the left. Figure from Yamamoto and Phipps Morgan (2009).*

For the refracted plume scenario, when the plume passes beneath the oblique FZ, a "roll-like" instability is introduced into the melting region, resulting in a strongly time-dependent pattern of melt-production along the island chain. Episodic flare-ups of off-chain volcanism are seen, with no apparent preference for persistent volcanism on the younger or older side of the FZ as shown in Figure 6.2b.

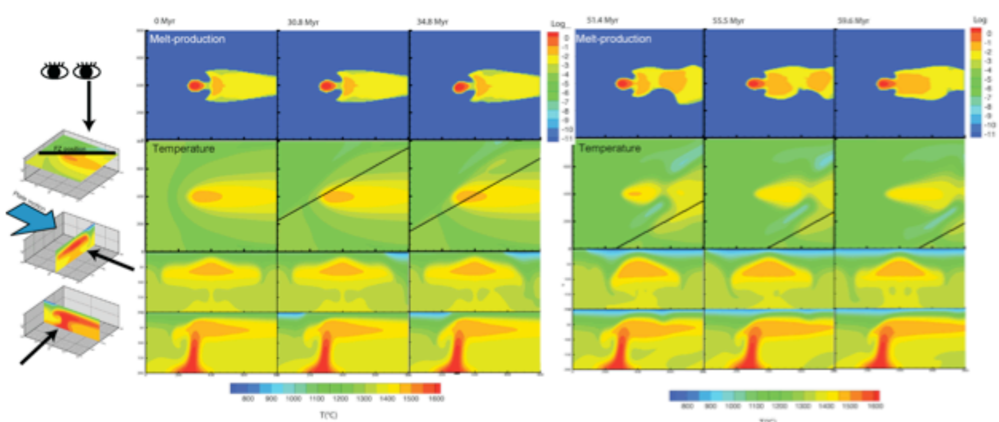

FIGURE 6.2B: *Snapshots showing the time-evolution of a refracted plume experiment for migration of an oblique fracture zone with a change in lithosphere thickness from 90km to 100km. This is the same experiment as Figure 6.2a except that the swell-root has only a temperature-dependent rheology that does not include the effect of melt-extraction-linked dehydration to increase the viscosity of the residual restitic material. Vertical sum of underlying melt production is shown in the top panels; lower panels show time-variation of the temperature field in the slices illustrated at the left. Figure from Yamamoto and Phipps Morgan (2009).*

In contrast, when the plume passes beneath an obliquely striking FZ in the restite-root hypothesis, there is a tendency for persistent volcanism on the young-age side as shown in Figure 6.2a and 6.1c. Similar spatial patterns of persistent melt production were predicted for several different age-offsets across the oblique fracture zone.

This example highlights the strong sensitivity of sub-lithospheric melting to the shape of the base of the overriding lithosphere, and the potential use of mapped patterns of surface volcanism to discriminate between possible mechanisms for the origin of hotspot swell relief. They also suggest that a promising future way to test between the restite-root and refracted plume models will be on the basis of their predictions for off- and on-chain patterns of volcanism after passage over an oblique FZ.

B. The Loa-Kea trend as an observational test for sub-lithospheric vs. lithospheric controls on hotspot volcanism

A curious aspect of recent Hawaiian volcanism is that is manifests as two subparallel trends of volcanic edifices, a Loa trend containing Loihi-Moana Loa and a Kea trend containing Kilauea-Moana Kea. Elastic gravitational stresses from pre-existing edifices were used to explain the geometry of Hawaiian rift zones with an elegant analog jello model. This hypothesis has been more extensively explored with more complete numerical treatments. However, the idea of a top-down control of the intrusion geometry by gravitational stresses doesn't explain why the 'Loa' and 'Kea' volcanic trends should be associated with distinct geochemical signals, as they are. Two ideas have been proposed to create this chemical contrast between the Loa and Kea sources: (1) A 'spaghetti' plume model with persistent lateral compositional 'stripes' within the plume; (2) zoned melting between a hot plume-center and cooler plume-rim.

If melt-extraction in the central region of the plume does in fact lead to the formation of restite that is more viscous than surrounding asthenosphere, then the viscous buckling of this restite plume stem (Figure 6.3) may be another possible mechanism to create a Loa-Kea oscillation within a spaghetti-type mantle plume. Gravitational buckling of buoyant viscous jets has mainly been thought of in geodynamics as a possible origin for buckling of subducting slabs below 660 km. However, the same physics could lead to a periodic buckling instability in a buoyant restite stem created by ongoing plume melting beneath Hawaii (Figure 6.3).

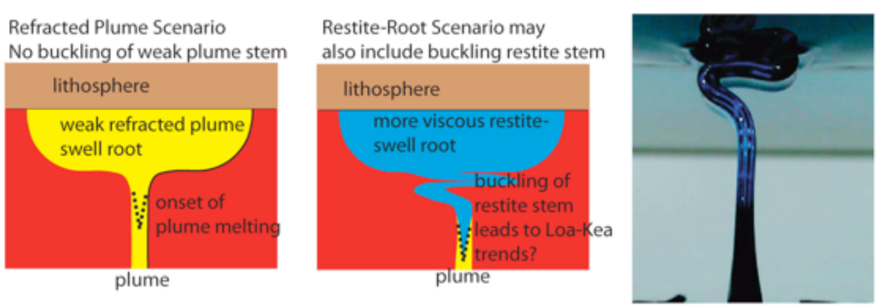

FIGURE 6.3: *What if there is a long skinny tail of restite being created by plume melting beneath Hawaii? Can this carrot shaped 'stem' (middle panel) buckle back and forth as in Ribe's model of the stiff sinking slab at a subduction zone (right panel). Only if the plume and plume-fed swell-root remain less viscous than surrounding asthenosphere (left panel) could this viscous bulking instability not take place. If stem buckling occurs at observed Loa-Kea rates for the same restite viscosity and plume-flux needed to reproduce the large-scale spreading of the Hawaiian Swell would be a strong new observation in favor of the creation of a more viscous restite root by Hawaiian plume melting. (rhs from Ribe (2003).*

With better lab and numerical experiments we will be able to test if in fact a more exact theory predicts the observed ~400,000 year buckling period for the same parameters that lead to ~5 Ma spreading of the swell-root. If true, this will be an important new constraint that would support the idea that dehydration melting of the mantle plume is creating a restite swell root beneath Hawaii and other hotspots with significant swells and superswells. The importance of this test is that spreading of a restite swell-root and buckling of a restite plume-stem obey different physics with different characteristic timescales, yet the different timescales depend on the same variables of restite flux, viscosity, and plate speed. If both timescales fit observed features of Hawaiian volcanism and swell relief, then this will be a strong argument that both processes are actually taking place beneath Hawaii.

C. Origin of Puka Puka Ridge Volcanism

The above examples have focussed on examples of intraplate volcanism that seem straightforward to link to a more complete theory of plume-lithosphere interaction. The ocean basins also contain clear examples of intraplate volcanism that are missing key aspects suggesting a simple plume link, for example episodic flare-ups of volcanism in linear volcanic structures that make up the Puka Puka ridges west of the East Pacific Rise. Possible mechanisms for this volcanism include melting linked to asthenospheric small-scale convection whose planform is shaped by Pacific plate motion, melting linked to small yet pervasive stretching of the Pacific lithosphere, and melting associated with ridgeward asthenospheric flow linking plume supply of asthenosphere beneath Polynesian hotspots to the asthenosphere consumption along the East Pacific Rise that is creating new oceanic lithosphere. Another hypothesis for this form of intraplate volcanism is that it is created by a feedback between melting and upwelling due to the fact that melting reduces the density of both the solid and liquid parts of partially-molten peridotite. Numerical experiments of this effect demonstrate intriguing 'storm-like' convective instabilities and associated melting anomalies that migrate laterally through an asthenosphere at a threshold for incipient partial melting.

D. Volcanism at continental margins—lateral plume drainage, Wegener-flow, or edge convection?

Passive continental margins are often volcanically active long after the initial rifting event. East Australia provides a fascinating example where this margin volcanism has migrated southward down the margin at the same latitudes and rate as a chain of plume-linked deep kimberlite-like (leucitite) volcanic centers erupted in the interior of the continent. (Figure 6.4). This time-synchronous migration suggests a possible origin linked to plume drainage from the interior of the continent towards its nearest margin. Other examples of this are found in Southeast Brazil (linked to the Martin Vaz plume), Axel Heiberg Island (linked to Iceland plume), ~80-90 Ma volcanics within the Mississippi Embayment linked to passage of the Bermuda plume beneath North America, and the Camaroon line (possible drainage from interior African plumes).

Other mechanisms proposed for post-rift continental margin volcanism include edge convection driven by the lateral temperature contrast between adjacent thicker continental and thinner oceanic thermal boundary layer, and upwelling asthenosphere flow induced by a thick continental root 'plowing' through the asthenosphere, thereby inducing asthenospheric downwelling at its bow, and upwelling and decompression melting in its wake. These hypotheses all need better quantitative evaluation and assessment against this intriguing observational dataset.

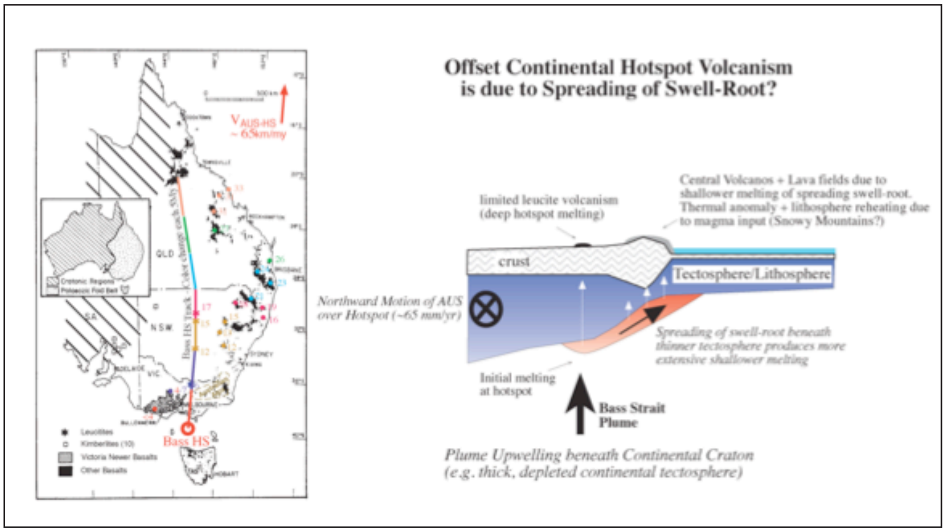

FIGURE 6.4: *Pattern of southward-migrating deep kimberlite-like and shallower coastal basaltic volcanism along the E. coast of Australia. (left panel) predicted backtrack for a Bass Strait HS using Dietmar Mueller's absolute motion history for the Indian Plate. Note how the eruption ages of observed deep-sourced leucitites fit this track very well. There are also coastal volcanics of similar age (color-coded in 5Ma intervals. A conceptual model of lateral plume drainage to explain this correlation is shown in the right panel. This model can be quantitatively tested to determine the viability of this flow/melting scenario both here and for a similar examples of time-progressive SE Brazilian coastal volcanics near Rio de Janeiro, on Axel Heiberg Island, the Camaroon Line, and the Mississippi embayment. Alternative mechanisms such as edge-driven convection or the Wegener 'wake-effect' from a moving continental craton also critically need to undergo better quantitative evaluations.*

E. Intra-plate Volcanism in Continental Interiors

Just as we would never have recognized the existence of plate tectonics without studying the tectonics of ocean basins, a better understanding of oceanic intra-plate volcanism is likely to provide significant insight into apparently more complex manifestations of intra-plate continental volcanism. Intra-plate volcanism linked to Yellowstone has persisted over the past 17 Ma, and has been associated with recurrent explosive volcanic eruptions that would be a significant natural hazard. Intra-plate continental volcanism has also been linked to many of the world's largest ore deposits. A particular form of rare deep explosive volcanism, kimberlite eruptions, has yet to occur within the historical record. Here, better understanding could lead to improved diamond prospecting and mining techniques. Flood basalt eruptions are fortunately even rarer than kimberlite eruptions. The consequences of these tremendous outpourings of magma are believed to include mass-extinction-linked changes in atmospheric and ocean chemistry. A better quantitative understanding of 'normal' intraplate volcanism is likely to lead to increased insights and ability to model these highly significant geodynamic events. Finally, since a volcano may well be the most visible evidence of mantle melting, the progress made in better quantification of the origins of intra-plate volcanism is likely to guide and shape improved understanding of large-scale mantle flow and melting. For example, do continental 'keels' plow through asthenosphere a bit like Wegener had imagined in continental drift, or is asthenosphere flow strongly coupled to surface plate motions, or does the asthenosphere flow beneath oceanic lithosphere at plate-like speeds or faster as a dynamic plume-fed boundary layer? Choosing between these different cartoon scenarios may well hinge on their predictions for intra-plate melting anomalies associated with these differing potential modes of mantle flow.

The Frontier

All of the focus problems just described are inherently multidisciplinary. Their solution requires better seismic observations, petrological and geochemical analysis, as well as geodynamic modeling of coupled flow, melting, and transport. A variety of promising approaches can be advanced to understand intra-plate volcanism in general. One approach is to formulate and explore the implications of 'ab initio' type rheological models of plume-asthenosphere-lithosphere flow that include more accurate and realistic physical and chemical parameterizations of rheology, buoyancy, melting, and melt-migration. To do this right we need to be able to build and test accurate 3-D models of these processes. This is central to understanding the problem of intraplate volcanism, and this central difficulty is a major part of why progress was so slow for so long, while ridges and trenches could be more profitably explored with 2-D idealizations and models. As the tools for 3-D modeling improve, the codes and insights obtained from study of intraplate volcanism can also be applied to some of the stickier questions concerning the dynamics of ridges and trenches that also require a 3-D approach. An alternative is to use observations of currently-unexplained patterns of intra-plate volcanism and uplift to formulate test problems, the idea being, if we can explain the observed natural variation in a self-consistent theory, we will gain confidence that the underlying theory is on the right track.

For the first approach, a quantitative theory of melting is needed to fuse geodynamic models for flow and temperature with petrologic and geochemical models of element behavior during the partial melting of rocks. Furthermore, we still are lacking a fundamental understanding of melt migration in the mantle. Our overall understanding of melt-migration, melt-rock reactions, and possible feedbacks between melt migration and mantle rheology is currently much less well developed than are mantle flow and melting treated separately. Because there are no simple solutions available to give partial insights into the coupled flow+melting+melt-migration problem, researchers have tended to over-idealize important aspects of this problem. For example, complexities associated with reactive melt migration are still commonly neglected, as are rheological complexities associated with a temperature and composition-dependent mantle+lithosphere rheology that has the potential to strongly shape flow, melting, and melt-rock interactions.

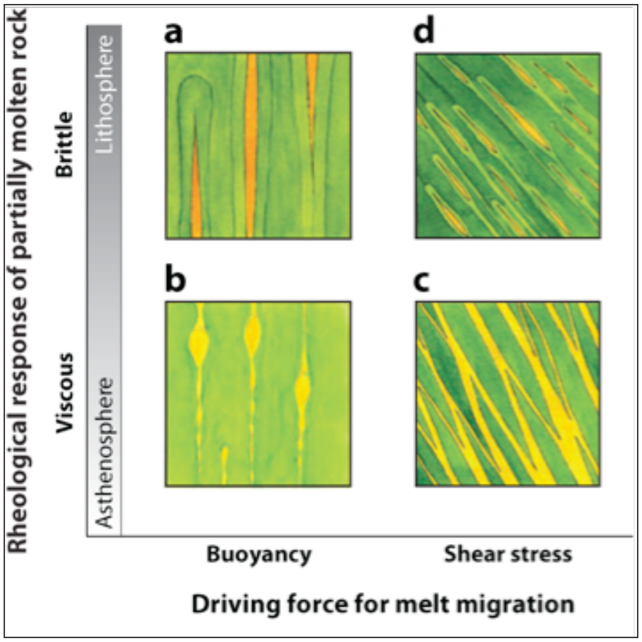

FIGURE 6.5: *Melt mechanism map. Mechanisms of melt migration through partially molten mantle rock are defined in terms of the driving force causing melt migration and/or melt segregation and by the deformation response of the rock. Driving force ranges from buoyancy to shear stress, while deformation response ranges from brittle to viscous. The vertical axis corresponds to the Deborah number which is the ratio of the viscoelastic relaxation time of the matrix to the characteristic timescale of the melt migration process. If the characteristic timescale is less than the relaxation time, then the effective matrix rheology response to strains associated with melt migration will be elastic. The horizontal axis compares the gravitational energy released by ascending melt to the strain energy released by the matrix during melt migration. The melt-migration mechanism cartoons represent (a) dike propagation in the brittle regime, (b) porous flow and porosity waves in the viscous regime, (c) stress-driven melt segregation in the viscous regime, and (d) shear crack propagation in the brittle regime. The gradient bar indicates which processes are expected to dominate in the asthenosphere vs. lithosphere. From Kohlstedt and Holtzman (2009).*

Where our state of knowledge is currently progressing most rapidly is through intercomparison between lab experiments and computations. The area where observational constraints have begun to play a useful role is in the interpretation of possible melt+deformation-linked seismic anisotropy at ridges, rifts, and subduction zones. However, this area of frontier research has witnessed a recent explosion of ideas in rethinking the effects of melt-migration through the mantle. Figure 6.5 shows a recently-proposed 'phase diagram' of possible melt-migration mechanisms that can arise depending on the local relative importance of buoyancy, viscosity, and deformation. It seems likely that real-world melt migration may involve depth-dependent transitions between different dominant migration mechanisms implied by this diagram, yet we need better understanding to effectively begin to address these potential complexities.

The frontier we describe here applies not only to intra-plate volcanism, but to all types of terrestrial volcanism. It generality and its complexity demand consistent science strategy of model building, and comparison between model predictions, and observations. Progress towards a more complete understanding of these manifestations of intra-plate volcanism will need substantial technical developments and some organizational developments as well, including:

- An interdisciplinary research focus on the rheology of the lithosphere-asthenosphere transition. Here improved geodynamic experiments need to be part of an effort that includes seismic imaging and mineral and rock physics studies of the rheology of lithosphere and asthenosphere.

- Improved computational approaches for 3-D variable viscosity flow.
- Improved theoretical and computational ability to determine thermodynamically consistent mantle melting, melt-solid reactions, and the behavior during partial melting of critical trace constituents such as water.
- Improved computational toolboxes and high-performance computing access to make the use of low-effort 3-D geodynamic numerical experiments achievable, so as to further augment the quantitative modeling capacity of the geodynamic research community.

Further Reading

A recent report of plume-like structures in the deep mantle below Hawaii:

Wolfe, C.J., Solomon, S.C., Laske, G., Collins, J.A., Detrick, R.S., Orcutt, J.A., Bercovici, D., and Hauri, E.H., 2009. Mantle shear-wave velocity structure beneath the Hawaiian hotspot, Science 326: 1388-1390.

A recent paper discussing the dynamics of melting-flow feedbacks on asthenospheric flow and melting:

Hernlund, J.W., P.J. Tackley, and D.J. Stevenson, 2008. Buoyant melting instabilities beneath extending lithosphere: 1. Numerical models, J. Geophys. Res., 113, B04405, doi:10.1029/2006JB004862.

A review of current ideas on melt segregation and melt migration processes in the mantle:

Kohlstedt, D. L., and B. K. Holtzman, 2009. Shearing melt out of the Earth: An experimentalist's perspective on the influence of deformation on melt extraction, Ann. Rev. Earth Planet. Sci. 37, 561-593.

A paper discussing folding of viscously deforming sheets, and its potential application to mantle deformation processes:

Ribe, N.M., 2004. Periodic folding of viscous sheets: Phys. Rev. E, v. 68, 036305.

A joint model/observation study using the observed geometry of volcanism linked to fracture zones to test three-dimensional numerical experiments on different scenarios for plume-lithosphere interaction:

Yamamoto, M., and J. Phipps Morgan, 2009. North Arch volcanic fields near Hawaii are evidence favouring the restite-root hypothesis for the origin of hotspot swells, Terranova, 21, 452-466.

7. Earthquake Dynamics

Few geodynamical processes have such direct and immediate impact on human populations as earthquakes and tsunamis. Earthquakes occur suddenly, usually without warning. The largest, most destructive earthquakes are rare events, yet these few events release most of the seismic energy of the Earth. The geodynamical challenge to mitigation of these hazards is understand the basic physical processes that cause earthquakes and tsunamis, so that meaningful predictions can eventually be made.

Milestone Accomplishments

Plate tectonics provides us with a very general explanation for most earthquakes, in terms of the three basic types of relative motion at plate boundaries, and their associated stress regimes, shown in Fig. 7.1. Extensional deformation at oceanic spreading centers and continental rift zones is accommodated by normal faulting; horizontal motion across transcurrent plate boundaries occurs by strike-slip fault motion, as on the San Andreas fault system, and compressional deformation at convergent plate boundaries results in thrust faulting. This later environment produces the largest earthquakes and the largest tsunamis. In contrast, only about 1% of all seismicity occurs away from plate boundaries, although the actual hazards posed by intra-plate seismic events are greater than their numbers would suggest, because many of these occur in heavily populated regions.

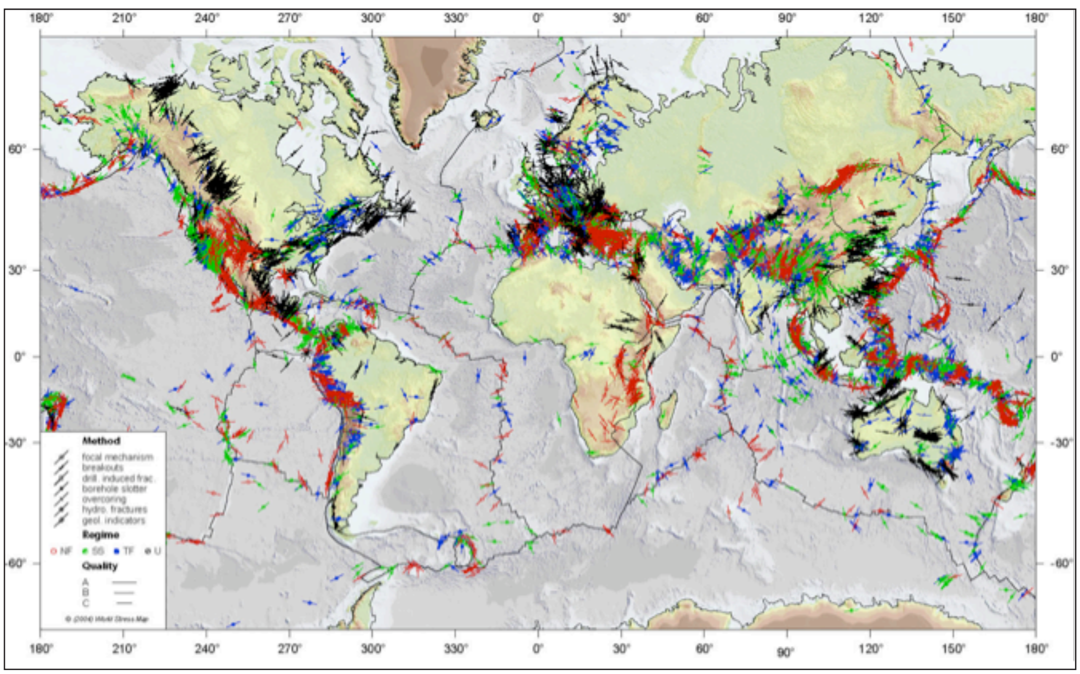

FIGURE 7.1 *World Stress Map Project 2005 distribution of stress in the crust. Line segments represent the direction and magnitude of maximum horizontal stress, line thickness proportional to data quality. Red, green, blue indicate normal, strike-slip, reverse faults, respectively. (based on Zoback, 1992); 2005 map:* **http://www.world stress-map.org**.

The concept of an earthquake cycle has proven to be a useful starting point for understanding earthquake dynamics. During most of this cycle, plate boundary faults systems are locked by static friction, while the background motion of the adjacent plates deforms the lithosphere in the fault zone region, increasing the density of elastic strain energy. As some point, the static frictional strength of the fault system is exceeded, the fault system begins to slip, and a portion of the accumulated strain energy is released. Part of this energy propagates as seismic waves, the earthquake, while some is converted to heat and some goes into uplifting and permanently deforming the crust.

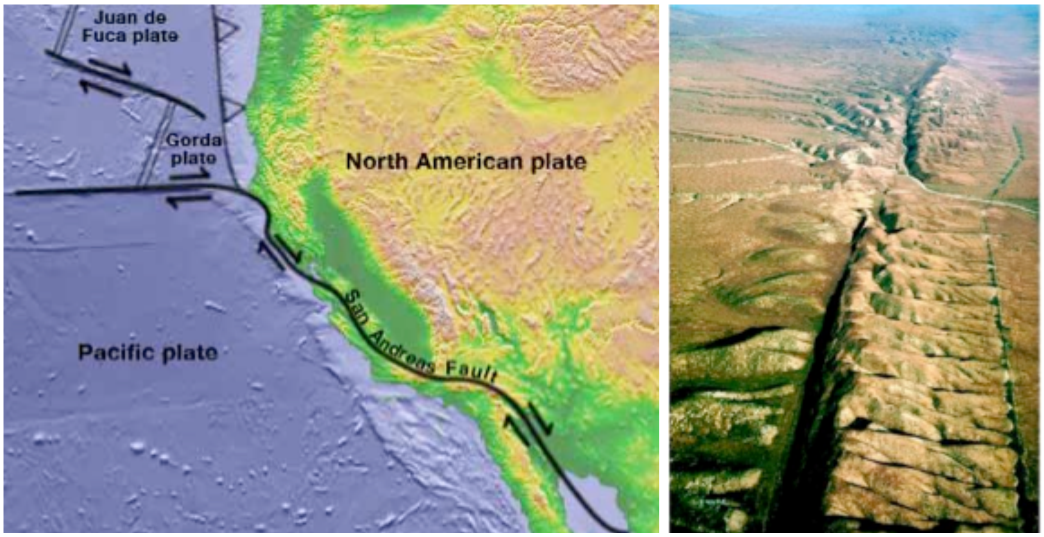

FIGURE 7.2: *The San Andreas is the best-studied fault system on Earth. It forms a part of the boundary between the North American and Pacific plates, as shown on the left. The relative motion across this fault is almost entirely right-lateral strike slip. As shown on the right, the trace of the San Andreas is clearly evident in the stress-induced topography in Central California.*

Unresolved Problems

Geodynamics will continue to play a vital role in the interdisciplinary search for the best earthquake hazard mitigation strategies and the ultimate goal of earthquake prediction. The route to these goals includes fundamental research on earthquake dynamics. The following are some key questions that geodynamics seeks to answer:

- What physical processes govern the strength of faults at various phases of the earthquake cycle?
- What role is played by volatiles (e.g. water and other fluids) in terms of earthquake triggers, transient creep, and dynamic weakening of faults?
- What is the relative importance of fault dynamics versus pre-existing structure and heterogeneity?
- How are individual earthquakes related to long term evolution of plate boundary regions?
- What determines the transition from stick-slip behavior to steady sliding on active faults?

- Is there a precursory stage for rupturing faults?
- How does the behavior of distributions of faults differ from the behavior of individual faults?
- How do geodynamical phenomena such as tremor and slow earthquakes relate to the earthquake cycle?

Background

The main goal of earthquake prediction is to determine where major earthquakes will occur and when. The where part of this question is already understood on a global scale, based on the statistics of earthquakes in the plate boundary regions described above, and the observed distribution of motion and stress in the crust. The when part of this question is far more difficult to answer.

The geodynamics approach to prediction is to develop a better understanding of the earthquake physics. This is a formidable challenge, given the vast spectrum of scales involved, ranging from the behavior of a few crystal grains at the fault tip to plate-scale blocks thousands of kilometers in lateral dimension. The spectrum of time scales involved is similarly broad, ranging from milliseconds for rupture nucleation to thousands of years for post-seismic relaxation. With so many overlapping physical processes, and because individual earthquakes are uniquely subject to the local geology, statistical approaches derived for irreducibly complex phenomena are sometimes used for prediction purposes. Nevertheless, significant advances have been made in terms of physically deterministic models, especially in the following areas.

Fault Zone Processes

Here the overarching goal is to understand the structure and dynamics of fault zones, including how the micro-scale processes that determine their rheologies produce the macroscopic behavior of fault systems. A variety of small-scale physical phenomena are understood to be important in active fault zones, such as pore-water pressure and flow, diagenetic alteration of minerals, stress-induced solution and dissolution, micro-fracturing other damage processes, gouge formation and alteration. What is unknown is how these small scale phenomena affect earthquakes.

Key Questions:

1. What crustal properties and processes govern fault weakening versus fault strengthening? How do these properties vary with temperature, depth and rock type?
2. Does fault strength change with slip during initiation of fault rupture? How important are dilatancy effects and fluid-transport to the slip nucleation process?
3. How important is continuous fault damage and how should damage be represented in fault dynamics models?

4. How do fault behaviors depend on micro-scale heterogeneity (i.e., roughness) map-scale heterogeneity such as offsets, bends, and irregularities in gouge and porosity? Can these effects be parameterized in terms of universal rate- and-state rheology laws?
5. How do faults heal? What small-scale processes govern the healing rate, and how do they depend on rock type, stress, pore fluids, and temperature?

Rupture Dynamics

Here the overarching goal is to understand the physics of rupture nucleation, propagation, and arrest, in actual fault systems, the processes that produce the destructive strong ground motion during earthquakes. Rupture on faults can be described in terms of relative displacements across the fault, or alternatively, in terms of the stresses in the crust. The first approach, usually termed kinematic, is the simpler and more traditional one. The second approach, usually termed dynamic, is far more complex but because it entails consideration of the rupture process it offers more predictive power.

Dynamic rupture modeling is an area of active research development. It is extremely challenging as a computational problem, due to the overlapping physical processes and the wide range of spatial and temporal scales involved. Dynamic rupture models applied to earthquakes typically use a parameterization of the fault slip nucleation process, combined with the past seismic history plus measured rates of tectonic deformation for each region. Plate tectonics provides the far-field boundary conditions, in terms of relative plate motions. Other inputs are the local crustal structure, including the fault network, and the elastic and viscous properties of each major rock unit. An important concept in rupture dynamics applied to earthquakes is the concept of seismic triggering. Laboratory studies of earthquake nucleation suggest there is an aseismic precursory phenomenon to fault slip, although too little is known about this phenomenon at present.

Key Questions:

1. How do earthquakes nucleate?
2. What threshold stress is necessary to initiate fault rupture?
3. How can measurements of fault friction from laboratory experiments be reconciled with the observed earthquake energy budget?
4. What are the mechanisms for the near-field and far-field dynamical triggering of smaller earthquakes by larger ones?
5. What factors limit fault-rupture propagation?
6. How should geodetic measurements of crustal deformation be used in seismic hazard assessment? How can these measurements be combined with geologic and paleoseismic data to infer earthquake recurrence rates?

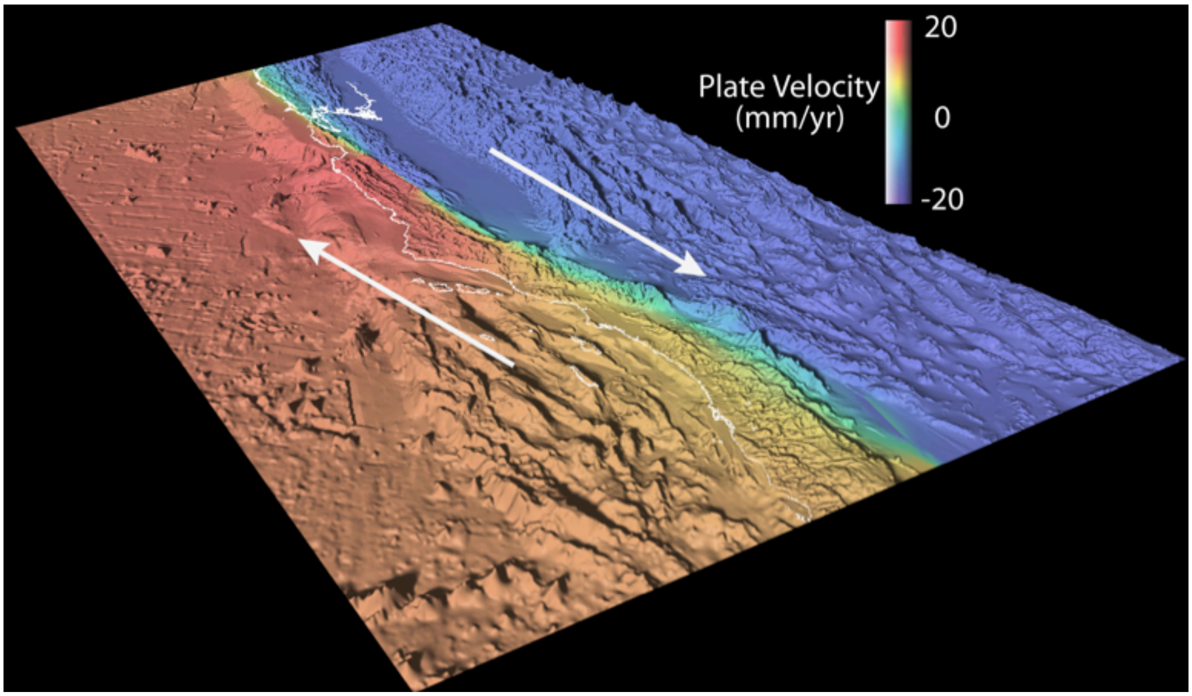

FIGURE 7.2: *The pattern of present-day deformation along the San Andreas Fault System. View is toward the northwest, the coastline shown in white. Contours are mm/yr of relative crustal motion. One of the primary goals in earthquake dynamics is to connect this kinematic pattern of plate motions to the stress in the crust and the distribution of earthquakes and stable sliding along the fault system. (from Smith-Konter and Sandwell, Geophys. Res. Lett., 36, 10.1029, 2009., courtesy B. Smith-Konter)*

Earthquake-earthquake Interactions

It is well established that aftershock events follow large shallow earthquakes, these having been triggered by the stress changes caused by the large event. Similarly, large earthquakes sometimes trigger other large earthquakes. A variety of mechanisms have been proposed to account for these phenomena, in addition to linear changes in elastic strain, including the flow of pore fluids, viscoelastic relaxation, and nucleation via time-dependent friction. Here is fertile ground for multi-scale geodynamics research, to explore the various interactions between the processes.

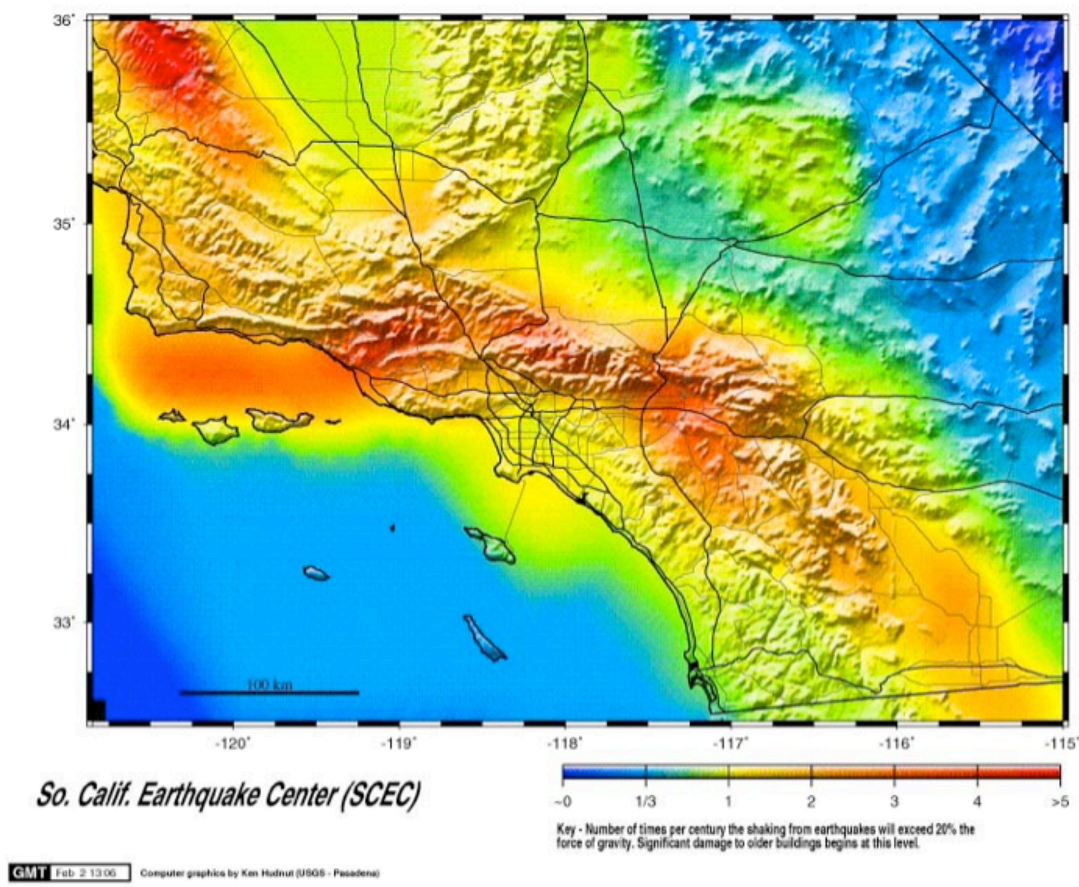

FIGURE 7.3: *The Southern California Earthquake Center (SCEC) seismic hazard map for the Los Angeles area. Contours are predicted frequency of strong motion (probable number of acceleration events exceeding 20% gravity per century). The geodynamical approach to earthquake prediction uses the relative plate motion from Fig. 7.2 as input to a dynamic crustal deformation model to produce "first-principles" seismic hazard maps such as this one. (Courtesy: K. Hadnut, USGS-Pasadena)*

Tsunami Generation, Propagation, and Run-up

Tsunamis are long wavelength ocean waves generated by undersea earthquakes and landslides. The magnitude of a tsunami increases with the earthquake size (seismic moment) but also depends on the fault orientation, the local seafloor topography and the fact that submarine landslides often accompany large undersea earthquakes.

Tsunamis propagate slower than seismic waves by a factor greater than 10, which provides the basis for early warning systems, as has been used successfully in the Pacific Basin for decades. The 2004 Sumatra tsunami shown in Fig. 7.4 that led to over 200,000 deaths, convinced the world to extend the Pacific warning system to the Atlantic, Indian, and Caribbean Oceans.

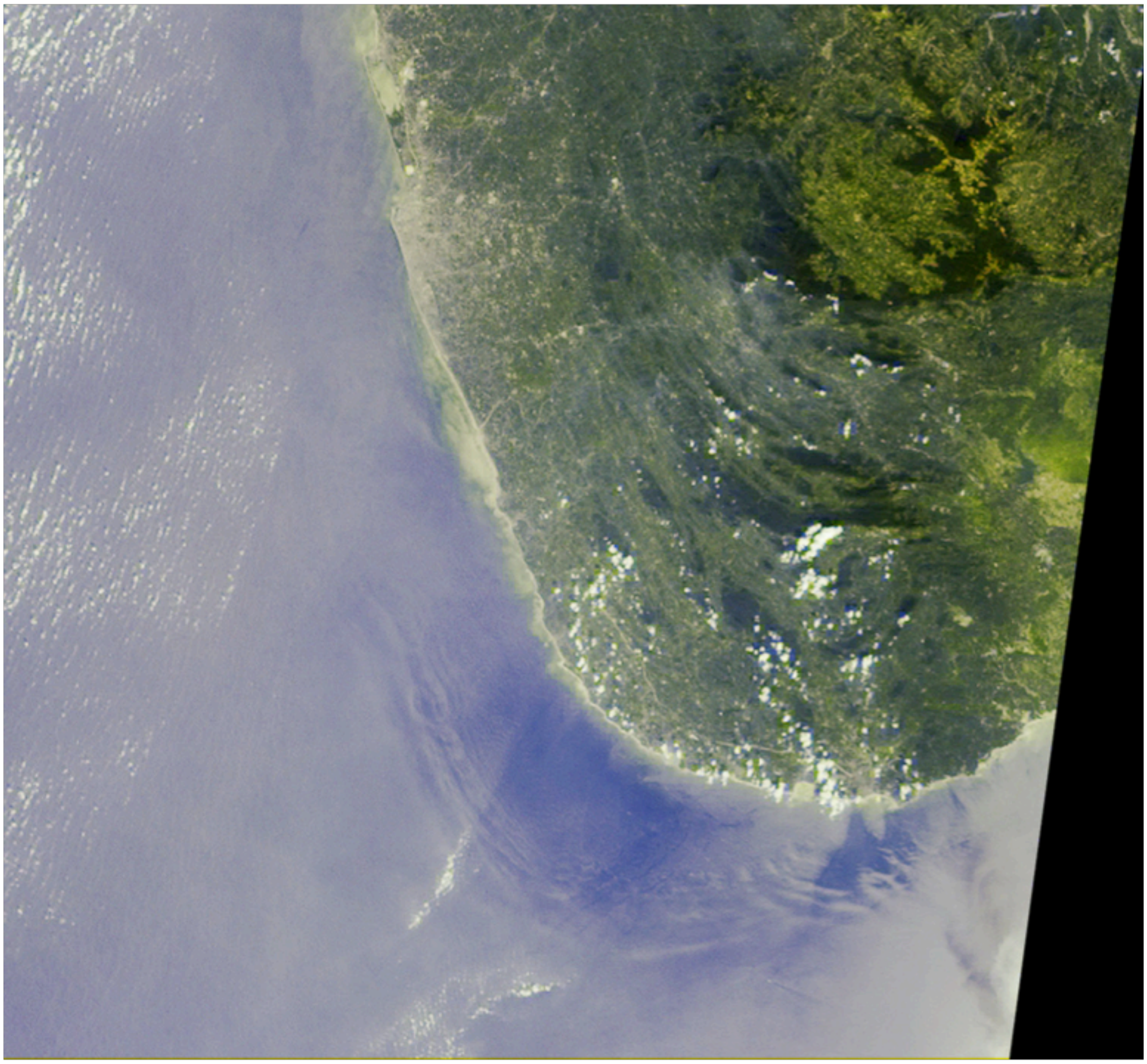

FIGURE 7.4: *Tsunami waves resulting from the 26 December M=9.1 Sumatra undersea earthquake. The wave train shown here took a little over 2 hours to reach Sri Lanka. Additional waves continued to arrive for many hours afterward. NASA's Terra satellite with its Multi-angle Imaging SpectroRadiometer (MISR) captured this image of deep ocean tsunami waves about 30-40 kilometers from Sri Lanka's southwestern coast. The waves are made visible due to the effects of changes in sea-surface slope on the reflected sunglint pattern. Courtesy: NASA*

Tsunami propagation in the open ocean is reasonably well understood, as they follow the tenants of shallow water wave theory to a good approximation. However, there remain outstanding problems concerning their undersea excitation, and the wave amplitudes during costal run-up, particularly where complex shorelines and undersea topography are present.

Future Goals

In terms of modeling, the crustal dynamics community is now moving away from generic, idealized geometries and crust rheologies, toward increasingly realistic geometries that feature multiple, non-planar and intersecting fault surfaces with heterogeneous crust in between. This trend is likely to continue as the focus shifts from idealized elastostatic approaches toward more complex models capable of making useful predictions for real seismically active regions.

One theoretical goal in earthquake dynamics is to link the two fundamental steps in the earthquake cycle that operate on widely different time scales: the decades or centuries long quasi-static inter-seismic phase, and the millisecond to tens of seconds dynamic rupture phase. Currently, these phases are usually treated separately. Another important goal is to develop the capability to simulate multiple earthquake cycles for realistic fault geometries and crustal structures, with sufficient resolution to capture strain accumulation and release, including propagating ruptures that radiate seismic waves, and post-seismic relaxation of the crust. A third important goal is to develop capacity for the assimilation of seismic and geodetic data into earthquake rupture models. Data assimilation into dynamical rupture simulations, in the form of surface topography, geologically-inferred slip rates, measured geodetic deformation, historical earthquakes, and laboratory-based rock friction laws, can greatly increase the predictive power of crustal dynamics models.

Further Reading

The following is a short list of books, review articles, and a few of the classic papers on earthquake dynamics and related short-term crustal dynamics.

Books and Review Papers

Earthquake Seismology, v4 Treatise on Geophysics, Kanamori, H. vol ed.; Schubert, G. series ed. Elsevier B.V., 2007.

International Handbook of Earthquake and Engineering Seismology, Lee, W. Kanamori, H.,, Jennings, P. and Kisslinger, C (eds) London: Academic Press, 2003.

Physics of Earthquakes, Geophysical Monograph 106, Rundle, J., Turcotte, DL., and Klein, W. (eds) Amer. Geophys. Un. Washington DC, 2000.

Scholz C.H., The Mechanics of Earthquakes and Faulting, 2nd ed. 496 pp. New York: Cambridge University Press, 2002.

Kanamori, H. and Brodsy, E.E., 2004. The physics of earthquakes. Reports progress in physics, 67: 1429-1496.

Classic and Recent Papers

Andrews, D.J., 2005. Rupture dynamics with energy loss outside the slip zone, J. Geophys. Res. 110: B01307.

Byerlee, J, 1978. Friction of rock. Pure and Applied Geophysics 116: 615-626.

Dahlen, F.A., 1977. The balance of energy in earthquake faulting, Geo. J. Roy. Astron. Soc., 48, 239-261.

Dieterich, J.H., 1992. Earthquake nucleation on faults with rate-and state-dependent strength. Tectonophysics 211: 115-134.

Fialko, Y., Sandwell, D. Agnew, D., Simons, M., Shearer, P. and Minster, B. 2002. Deformation on neary faults induced by the 1999 Hector Mine earthquake, Science 297: 1858-1862.

Rice, J.R., 2006. Heating and weakening of faults during earthquake slip, J. Geophys. Res., B05311.

Smith-Konter, B., and Sandwell, D.T., 2009. Stress evolution of the San Andreas Fault System: Recurrence interval versus locking depth, Geophys. Res. Lett., 36,doi:10.1029/2009GL037235.

Zoback, M.L, 1992. World Stress Map Project, J. Geophys Res. 97: 11703-11728 2005 map: http://www.world-stress-map.org

8. Geology of the Core-Mantle Boundary Region

The Challenge

The core-mantle boundary represents the most fundamental transition in Earth's interior. It separates the two giant heat engines, one in the metallic core that maintains the geodynamo, the other in the silicate-oxide mantle that drives global tectonics. The core supplies heat and possibly some mass to the mantle, whereas the mantle exerts the primary control over the rate and spatial distribution of the mass and heat transport, thereby controlling the evolution of the core. Here the challenge is to interpret the complex structure of the core-mantle boundary region and identify the geodynamical processes that continue to shape it.

Milestone Accomplishments

We now know that the core-mantle boundary region is not a simple discontinuity. Instead, its complex structure mirrors aspects of the geological complexity at the Earth's surface. Many near-surface processes have been invoked to explain the structural complexity in the core-mantle boundary region, including mountain building, magmatic activity, and even erosion and deposition. As our knowledge of the core-mantle boundary region steadily improves, the view that emerges is one of a dynamic environment where a large set of overlapping physical and chemical processes contribute to the evolution of our planet as a whole.

The lithosphere and core-mantle boundary regions share the role of thermal boundary layers at the top and bottom of the convecting mantle, respectively. Low temperature near the surface is responsible for the strength of lithospheric plates, a key component of plate tectonics. In contrast, high temperature at the base of the mantle is expected to produce a mobile, low-viscosity layer, which is distinct from the interior of the convecting mantle. However, the structural complexity of both regions far exceeds our expectations for a simple thermal boundary layer. There is ample evidence at both boundaries for compositional heterogeneity, melting, and crystalline texture due to large-scale deformation. In addition, pressure-induced phase transformations occur in both regions. For these reasons, geodynamicists have concluded that the processes at work at the top and bottom of the mantle have much in common.

Background

Most of the evidence for complexity at the core-mantle boundary comes from seismology. The earliest indications of unusual structure were found in the anomalous radial profiles of P (compression) and S (shear) wave velocities, leading Bullen in1949 to name this the D”-region. Subsequent observations of seismic and scattering established the presence of large-scale discontinuities in seismic properties, as well as small-scale heterogeneity. Modern tomographic imaging now provides a coherent view of seismic heterogeneity at the largest scales. All of the current global seismic tomographic models reveal sharp increases in the level of heterogeneity in the near-surface and also near the core-mantle boundary (Fig. 8.1). Efforts to explain this structure increasingly invoke some form of chemical heterogeneity to account for the unexpected anti-correlation between bulk and shear modulus. However, the origin and role of deep chemical heterogeneity in the broader framework of thermal convection is not well understood. Given that most of the chemical heterogeneity at the surface is connected with magmatism, there is a strong appeal for proposing similar processes at the core-mantle. Indeed there is growing evidence from regional seismic studies for partial melt in the deep mantle.

Regional seismic studies provide an important complement to global tomographic models, however, the fine-scale structure inferred from such studies offers a bewildering view of complexity near the core-mantle boundary (Fig. 8.2). Narrow layers with velocity reductions of 10% for P-waves and 30% for S-wave have been detected sporadically over the

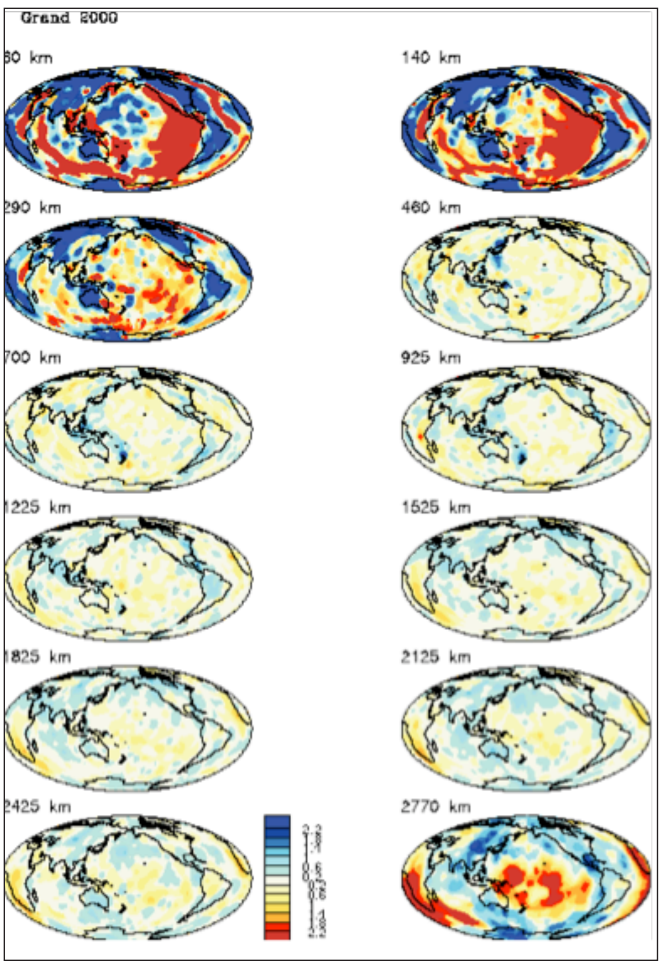

FIGURE 8.1. *Lateral variations in seismic shear wave velocity at various mantle depths, after Grand (2002). Note that the seismic heterogeneity is largest at the top and bottom of the mantle.*

core-mantle boundary, These so-called ultra-low-velocity zones (ULVZs) evidently have thicknesses of a few tens of kilometers and exhibit strong lateral variations over distances of a few hundred kilometers. ULVZs are often attributed to the presence of partial melt, although a host of other interpretations have been proposed. Increases in data coverage through USArray and other initiatives have enabled new processing techniques that reveal pervasive layering and a complex distribution of seismic anisotropy. For example, it is found that coherent seismic reflectors exhibit substantial variations in height above the core-mantle boundary. Substantial variations are also reported in the structure of the seismic anisotropy. Horizontally polarized S waves typically travel faster than the vertically polarized S waves in most of the D” region, although the amplitude of this anisotropy appears to vary laterally. There is also evidence for azimuthal anisotropy, possibly due to tilting of a predominantly transverse fabric.

Core-Mantle Boundary Region Dynamics

All this structural complexity provides clues about the dynamical processes that operate near the core-mantle boundary. For example, chemical heterogeneity at the base of the mantle is sometimes attributed to segregation of the crustal component from subducting slabs. In this case, the volume of chemically distinct material constrains the efficiency and duration of crustal segregation, which has important implications for the onset of plate tectonics and the interpretation of isotopic heterogeneity. Other researchers propose that the distinct chemical component is a product of early differentiation. Material that is too dense to be entrained into the overlying convection would likely reside at the base of the mantle over the age of the Earth, according to this interpretation. In either case, large-scale flow in the overlying mantle has the potential to sweep this material away from regions of downwelling due to subduction, and to build large, high-density piles. Tectonic stresses and the negative buoyancy of these piles are expected to produce the topography on the core-mantle boundary, which can alter flow in the core in much the same way that mountains influence atmospheric circulation.

There are important chemical questions as well. A close analogy to continental crust is suggested by the capacity of the core-mantle boundary region to sequester radiogenic heat-producing elements. A repository for heat-producing elements at the base of the mantle could solve the long-standing mystery of missing heat sources, based on expectations from cosmochemical abundances. Resolving the question of missing heat sources is important because our current understanding of the evolution of the Earth is seriously limited by uncertainties in the abundance and distribution of these heat-producing elements.

Melting and magmatic processes may also play a role at the core-mantle boundary. The existence of melt is supported by the presence of ULVZs. A dense melt (relative to the residual solid) is expected at high pressure and temperature. The resulting buoyancy would explain why ULVZs reside at the base of the mantle. In fact, melt may erupt (downward) to the core-mantle surface and accumulate in topographic “depressions” in the boundary. The challenge of retaining a dense partial melt in the mantle to explain the existence ULVZs remains an

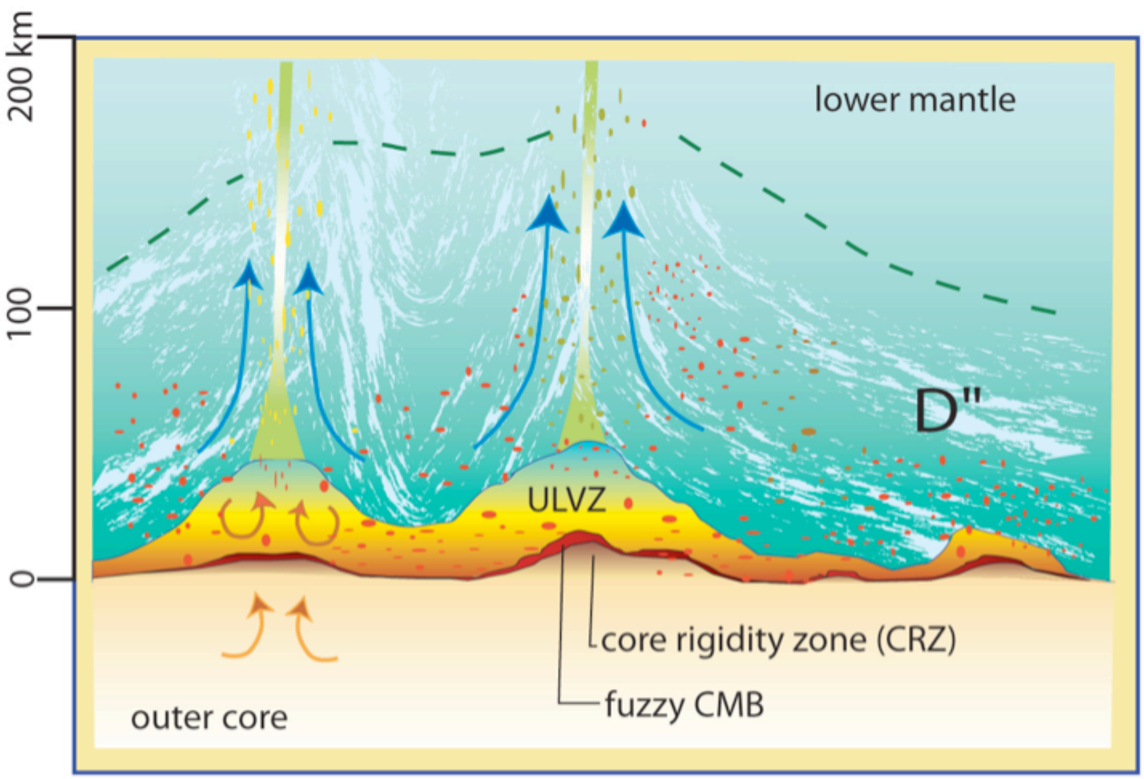

FIGURE 8.2: *Schematic illustration of the complex structure and diverse processes near the core-mantle boundary (after Garnero, 2000).*

unsolved problem. Even the origin of the melt is uncertain. Delivery of volatiles in subducting slab may initiate melting by locally depressing the melting temperature, much like melting above subduction zones. Alternatively, the melt may be a remnant of a more pervasive magma ocean at the base of the mantle. Heat from the core is expected to buffer the cooling of the melt over geological time. Gradual cooling and crystallization could potentially explain the compositional heterogeneity inferred from seismological observations.

Several other processes are expected to contribute to the complexity of the core-mantle boundary region. The recent discovery of a new pressure-induced phase transition from silicate perovskite to a denser post-perovskite phase is still reverberating, as researchers strive to understand its full dynamical consequences. Experiments and theory suggest that the phase transition occurs several hundred kilometers above the core-mantle boundary, which is compatible with the location of a known seismic discontinuity at the top of D". Even the magnitude of the seismic discontinuity is broadly consistent with theoretical estimates of the mineral properties. Because this transition occurs close to the thermal boundary layer, the steep increase in temperature may cause the post-perovskite structure to revert back to perovskite, producing a secondary seismic reflection close to the core-mantle boundary. Detection of a consistent pair of seismic reflectors appears to support the presence of the second transition. Knowledge of the phase diagram constrains temperature at the depths of these two transitions while the mantle flow induced by the dense post-perovskite is expected to elevate the local heat flow at the core-mantle boundary.

Processes analogous to chemical weathering are also possible at the core-mantle boundary. Chemical equilibrium is expected at the contact between liquid iron and silicate minerals at the base of the mantle by virtue of the high temperature, although the composition of this contact does not necessarily reflect the bulk composition of either the core or the mantle. Rapid convection in the core is capable of mixing the core on timescales of 104 years, whereas the mixing in the mantle is considerably slower. Gradual changes in the composition and temperature of the core due to cooling and inner-core growth continually disturb the contact, inevitably causing chemical interactions to restore equilibrium. More rapid interactions are possible in the presence of topography on the core-mantle boundary because small variations in the pressure and temperature over the surface alter the local equilibrium. Convective mixing in the core can homogenize the composition of the core, leading to persistent disequilibrium at the peaks and valleys in the boundary. One possible outcome is a steady chemical erosion (or filling) of topographic features. Experimental efforts to constrain the chemical equilibrium between mantle minerals and liquid iron may soon enable geodynamic models to make testable predictions.

Unresolved Issues

Many fundamental questions about the core-mantle boundary have been posed, but as yet we have very few definite answers. A partial list of the questions raised in the preceding discussion include:

- What parts of core-mantle boundary region structure are due to thermal, chemical, and phase transformation heterogeneity?
- How large is the heat flow across the core-mantle boundary, and what is its spatial variation?
- Are there partial melts in this region, and if so, what is their dynamical behavior?
- Are there dynamically important concentrations of radioactive heat producers present?
- How large is mass exchange between the core and mantle, and what are the important species involved?
- What accounts for the observed negative correlation between seismic bulk and shear velocity in this region?
- Do mantle plumes originate from the core-mantle boundary region?
- What is the flux of slab material into this region?
- What roles do chemical reactions and erosion/deposition processes play in shaping the core-mantle boundary region?

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9. Origin of Earth's Changing Magnetic Field

The Challenge

Mankind lives within a giant magnetic shield. The geomagnetic field surrounds the Earth like a tenuous bubble and provides our first line of defense against bombardment of high-energy charged particles from the sun. We know that the geomagnetic field has persisted for more than three billion years, the result of a self-sustaining fluid dynamo operating within the Earth's core. Here the grand challenges are to understand how the dynamo process sustains the geomagnetic field inside the core, how this process is coupled to other parts of the Earth system, what causes the geomagnetic field to change so dramatically with time, how these changes affect the surface environment, and what are the implications of past and presently-active dynamos in other planets.

Milestone Accomplishments

Because it was one of the primary means of navigation during the age of exploration, geomagnetic field directions have been charted for centuries. In addition, the magnetization acquired by igneous rocks, sediments, as well as man-made artifacts, provide records of the geomagnetic field over time scales ranging from thousands to hundreds of millions of years. These records display a remarkable spectrum of change, including extreme events such as magnetic polarity reversals, where the magnetic shield first weakens and then transitions from a dipolar-type configuration to a transitional configuration before returning to its previous state with a reversal in direction.

Despite a long history of observations, the role of the geomagnetic field in geodynamics is a relatively young subject. Well into the 20th century, theorists routinely listed the origin of planetary magnetic fields among the top unsolved problems in physical science. Recently, the prospects for understanding the geodynamo have undergone a transformation, thanks to three important advances. First, we are now able to simulate the dynamo process numerically, starting from the basic principles of magnetohydrodynamics as they apply in the Earth's core. Second, laboratory examples of self-sustaining fluid dynamos have been constructed, using large volumes of liquid sodium, a technology originally developed for breeder nuclear reactors. And third, spacecraft exploration has considerably increased the inventory of known planetary dynamos.

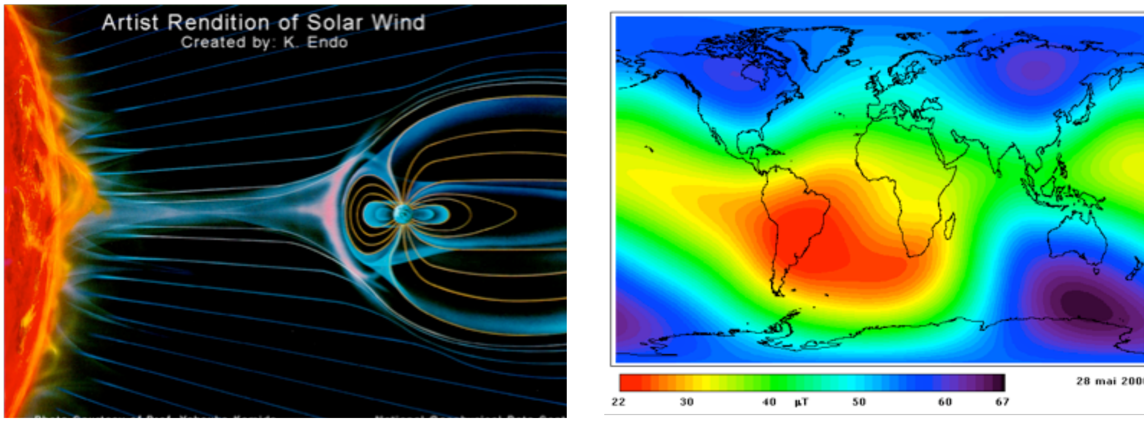

FIGURE 9.1: *Earth's magnetic shield. Left: Schematic illustration of the solar wind interaction with the external geomagnetic field. The solar wind distorts the inclined geomagnetic dipole field, producing the upstream bow shock and downstream magneto-tail structures. Charged particles from the solar wind enter the Earth system along geomagnetic field lines; some of these particles are trapped in dark blue shaded radiation belts. [K. Endo, Courtesy: Y. Kamide and NOAA]. RIght: Contours of the intensity of the surface geomagnetic field at of epoch 2000 in µT (microtesla). The South Atlantic Anomaly (SAA) is the prominent low intensity region centered off the coast of Brazil. The weaker geomagnetic field allows enhanced radiation at spacecraft altitudes in this region (Benton et al., 2002) with possible human health risks (Palmer et al., 2006). The International Space Station requires extra shielding for the enhanced radiation and the Hubble Space Telescope does not take observations while passing through the SAA.*

Major Unresolved Problems

These new tools and observational capabilities offer an opportunity to address a host of unresolved issues about how the geodynamo process fits into the broader picture of whole-Earth dynamics. Major issues include:

- What is the energy budget for the geodynamo?
- What is the nature of convection and turbulence in the outer core?
- What are the causes and consequences of magnetic polarity reversals and excursions?
- Does the present-day dipole weakening portend a major transition, such as a reversal or excursion?
- How do mantle dynamics affect the core and the geodynamo process?
- How does the geomagnetic field influence near-surface environments?
- What are the similarities and differences between the dynamo process in the Earth and other magnetic planets?

Background

The geodynamo is the process by which kinetic energy of fluid motion in the outer core is continually transformed into magnetic field. We know that three basic ingredients are vital for this process: (1) a large volume of electrically conducting fluid, (2) a supply of energy to produce circulation and turbulence in that fluid, and (3) planetary rotation, which organizes the fluid motion so that the transformation of kinetic to magnetic energy occurs efficiently enough to overcome dissipative effects.

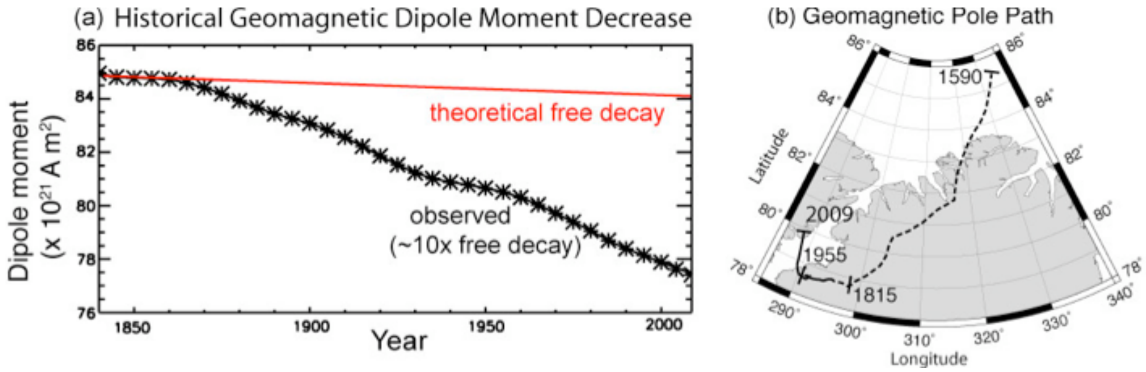

FIGURE 9.2: *Rapid changes of the geodynamo. (a) Observed decrease of the geomagnetic dipole moment since 1840, from Jackson et al. (2000) and Olsen and Mandea (2008). The historical average decay rate of the dipole is about 5.5% per century, (Finlay, 2008), 10 times its free decay rate. The dynamo process is dynamically extracting energy from the geomagnetic dipole over the past 170 years (Olson and Amit, 2006) suggesting (to some) a prolonged geomagnetic weakening event. (b) Observed motion of the geomagnetic pole in three stages: 1590-1815 when the pole moved south and the dipole axis tilt increased, 1815-1955 when the pole moved west and the tilt remained virtually unchanged, and 1955-2009 (continuing at present) as the pole moves mainly north and the tilt decreases. Rapid geomagnetic variations are caused by highly time dependent motions in the liquid outer core (Bloxham et al., 2002).*

Geodynamo Energetics

For the geodynamo, the iron-rich liquid outer core is the conducting fluid and its primary energy source is convection. Heat flow from the core to the mantle drives thermal convection in the liquid outer core and also causes the inner core to grow, as iron-rich solid crystallizes at the inner-outer core boundary. Inner core solidification also provides buoyancy for the convection, through the release of latent heat and the partitioning of relatively light elements such as sulfur and oxygen into the outer core. In addition to convection, other energy sources may contribute to the geodynamo, including instabilities in the outer core arising from Earth's precession and tidal forces.

Although we know that a substantial expenditure of energy is required to maintain the geodynamo, the actual amount remains controversial. The present-day heat loss from the core is highly uncertain, with estimates ranging from 4 TW to as high as 18 TW. The amount of heat leaving the core is critical to such fundamental issues as the age of the solid inner core and the heat transport by plumes originating in the lower mantle. For example, estimates of the age of the inner core age vary from 3 Ga to 0.4 Ga, depending on the core heat loss.

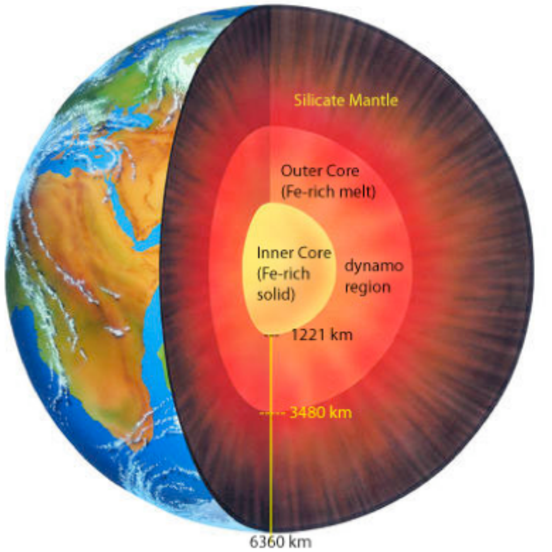

FIGURE 9.3: *Cutaway view of the Earth, showing its basic radial internal structure where the geomagnetic field is generated, including the mostly solid silicate + oxide mantle-crust system and the iron-rich electrically conducting core, the geodynamo region, sub-divided into the liquid outer core and the solid inner core. The core contains lighter elements such as S, Si, and O (Alfe et al., 2000; Porier, 1994), and exhibits dynamical coupling with the mantle (Buffett, 2003; Aubert et al., 2008) Heat flow from the core to the mantle, about 10 TW (Lay et al., 2008) is an important power source for the geodynamo and causes solidification of the inner core, which may be younger than 1 Ga (Labrosse et al., 2001; Nimmo, 2007). Other planets have diverse electrically conducting interior fluid regions (Stevenson, 1981).*

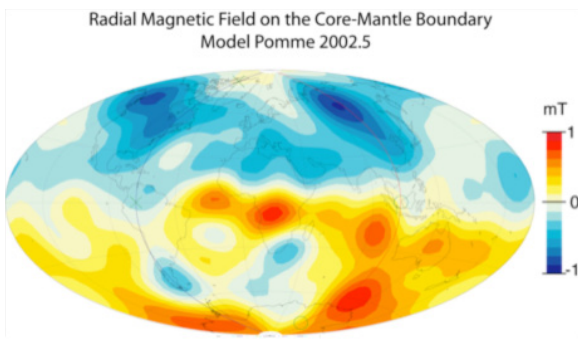

FIGURE 9.4: *The geodynamo at its source. Shown here are contours of the intensity of the radial component of the geomagnetic field on the core-mantle boundary in mT (millitesla), downward extrapolated from surface and spacecraft observations for epoch 2002.5 (Maus et al., 2004). Blue indicates inward-directed field, red indicates outward-directed field. Continental outlines are shown for reference. Earth's external dipole field is mainly derived from the four high-latitude, high intensity magnetic flux regions shown here, two in each hemisphere. The position of the geomagnetic dipole axis is shown by the green circle in the southern hemisphere near Antarctica, its northern projection by the cross near Greenland. Equatorial circle and cross denote the equatorial dipole axis. This figure demonstrates that the South Atlantic Anomaly (SAA) region of weak magnetic intensity at Earth's surface, is actually due to reversed magnetic flux beneath South America and South Africa. The future growth of the SAA is a target of dynamo model-based forecasting techniques (Kuang et al., 2008).*

Convection and Turbulence in the Outer Core

The nature of convection in the core differs from convection in other fluids in the Earth system. In the outer core, the forces arising from planetary rotation, strong magnetic fields, and buoyancy, interact over an enormous depth range, and the energy dissipation is by Joule heating, rather than by mechanical dissipation as in other geophysical fluids. Numerical models are able to simulate the largest scales of core flow. However, theory and experiments indicate that core flow is actually turbulent, even though the overall fluid velocity is rather small. The study of turbulence in the core is a relatively new subject in geodynamics, but we anticipate it will play an increasingly important role as models become more sophisticated.

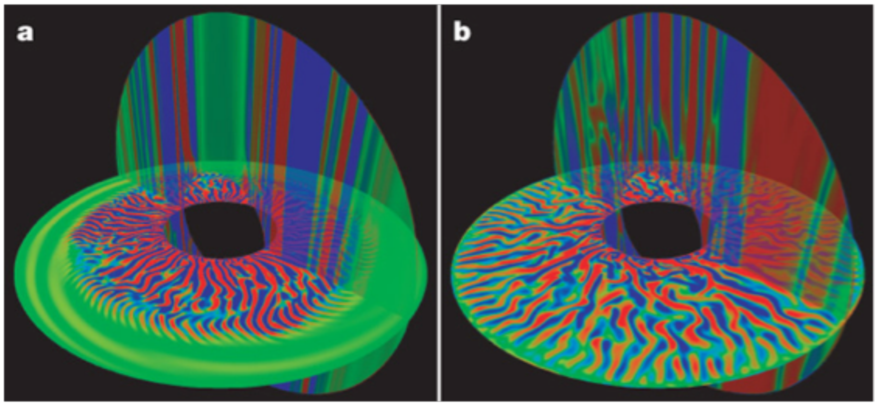

FIGURE 9.5: *Structure of convection in the outer core according to a high-resolution numerical dynamo model (Kageyama et al., 2008). Images show the structure of core convection in terms of the axial component of fluid vorticity (red=positive, blue=negative). Note the columnar structure in the axial direction and the fine-scale turbulent structure in the equatorial plane. The axial columnar structure results from strong rotational controls on the convection.*

Polarity Reversals

The fact that the geomagnetic field has stably persisted for most of Earth's history while repeatedly reversing its polarity is a strong constraint on the dynamo process. Key observations include the time required for polarity reversal (5-12 kyr), the highly variable duration of stable polarity chrons (50 kyr to 40 Myr) and the nature of the weak transition field during the reversals. In addition to full polarity reversals, the record shows many instances of aborted reversals called excursions. Numerical experimental models commonly show spontaneous polarity reversals and excursions, although we lack the ability to forecast reversals, and likewise, we know little about their consequences for the surface environment.

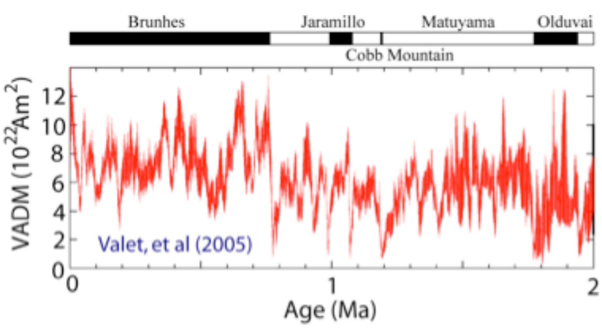

FIGURE 9.6: *Geodynamo reversals and excursions, 0-2 Ma. This record shows changes in the virtual axial dipole moment (VADM) obtained by Valet et al. (2005) from magnetization intensity of deep sea sediment cores, assuming the geomagnetic field consists of an axial dipole. Bar plot (top) shows the polarity record, with normal polarity (i.e., present-day polarity) magnetic epochs shaded, reverse magnetic polarity epochs un-shaded. Polarity reversals and excursions occur when the geomagnetic dipole is weak. The weak transition field may allow for solar wind heating of the atmosphere, although there is no substantiated connections between individual reversals and faunal extinctions (Plotnick, 1980).*

Core-Mantle Interactions

There is considerable interest in short-term and long-term interactions between the core and the mantle. For example, the core and mantle exchange angular momentum on decade time scales, although the mechanism for this exchange remains unclear. There is evidence for very long time scale interactions in the paleomagnetic record, typified by 40 Myr magnetic polarity superchrons and the 100 Myr modulation of reversal frequencies, which suggest the history of the geodynamo is linked to the tectonic history of the mantle and crust.

Recent progress

Numerical Dynamos

The use of first-principles numerical models of self-sustaining fluid dynamos has been the most significant technical development in the study of the geodynamo in decades, and has led to enormous progress in this arena. Numerical dynamo models are rapidly proliferating; at present, there are about two dozen research groups worldwide, including about a half-dozen US groups, using them to investigate planetary magnetic field generation throughout the solar system and beyond. How well do these models capture the geodynamo process as it actually occurs in Earth's core? At first glance the situation looks promising; numerical dynamos are able to reproduce many of the defining characteristics of the geomagnetic field, such as its inclined dipole external structure, secular variation, and spontaneous polarity reversals and excursions. Even so, a closer inspection reveals that many daunting challenges remain.

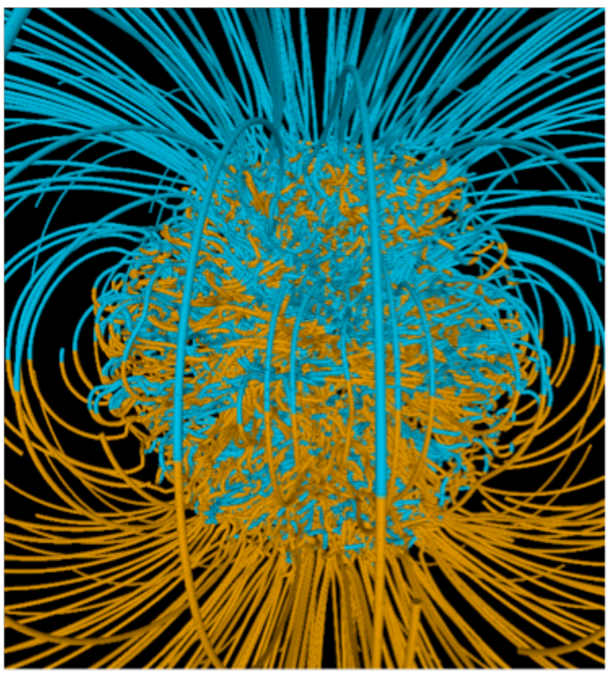

FIGURE 9.7: *Magnetic field lines from numerical dynamo model. Negative and positive radial field polarity shown as blue and yellow, respectively. The magnetic field inside the core has a complex fine structure due to turbulent fluid motions in the liquid outer core, whereas the field structure outside the core is less complex and more dipolar. These types of numerical dynamo models are now routinely used to explain many basic geomagnetic phenomena (Takahachi et al., 2005; Christensen and Wicht, 2007) although they fall short on several counts of being direct numerical simulations of the geodynamo process (Kono and Roberts, 2002; Glatzmaier, 2002). (Courtesy: G. Glatzmaier).*

Laboratory Fluid Dynamos

The goal of spontaneous magnetic field generation in a laboratory fluid dynamo was realized in 2000, when groups in Latvia and Germany reported dynamo self-generation in liquid sodium. Although neither experiment was particularly geophysical (in both, the sodium was pumped through networks of tubes and channels), they matched theoretical expectations and also served to motivate further experimentation. The next major advance occurred in 2006, when the VKS (von Karmen sodium) apparatus in France, a 0.6 m cylinder of liquid sodium in which turbulent flow is driven by two counter-rotating impellers, achieved a self-sustaining dynamo action (Monchaux et al., 2007), and later observed spontaneous polarity reversals. A third generation of laboratory dynamos are now under construction, some in the US, this time with the spherical geometry of the Earth's core. In order to reach dynamo conditions, the flow in these experiments will be driven mechanically, rather than by convection.

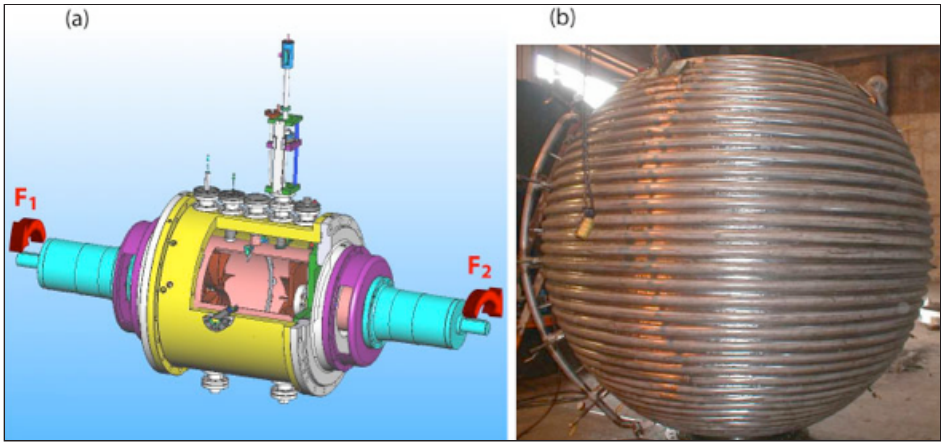

FIGURE 9.8: *Experimental liquid sodium dynamos. (a) Sketch of the VKS (von Karmen sodium) dynamo apparatus in France. This device achieved self-sustaining dynamo action in 2006 using a set of counter-rotating co-axial iron propellers (Monchaux et al., 2007) and later recorded polarity reversals. (b) 3 m diameter spherical shell dynamo apparatus undergoing testing at the University of Maryland (Courtesy: D. P. Lathrop).*

The Frontier

In spite of some recent advances, clearly defined frontier problems remain. For example, we still do not know how the geodynamo responds to the Earth's true rotation or the broad spectrum of turbulence expected in the Earth's core. Dynamics of the core is characterized by extreme values of the critical parameters; direct simulation requires models with presently unattainable levels of resolution in space and time. For this reason, geomagnetic forecasting relies on data extrapolation techniques, although assimilation approaches are now being tried. Experimentally, the frontier problem is to produce a laboratory dynamo in an Earth-like geometry, with rotation included. There remain severe technical difficulties associated with scale and power requirements before such experiments become a reality.

In terms of observations, new efforts are underway to better image the geodynamo and the dynamos in other planets. The international SWARM satellite constellation is scheduled to chart the geomagnetic field with enough precision to directly measure its secular variation at the core-mantle boundary, providing images of the geodynamo in real time, which hopefully will allows us to understand the present-day waning of the dipole field. The current NASA Messenger mission to Mercury and the scheduled Juno mission to Jupiter will provide close-up views of other active planetary dynamos in our solar system, and there is also the prospect of dynamo in extra-solar planets. In addition, there are coordinated efforts underway to systematically delineate the structure of the geodynamo through time, as preserved in the paleomagnetic record.

So far, these diverse approaches have progressed along somewhat separate tracks, with numerical models focusing mainly on larger-scale core processes, laboratory models focusing on smaller-scale core processes, and observations focusing on the external field behavior. There is an obvious need to bridge the gaps, in order for a full picture of this extraordinary phenomenon to emerge.

Research tools

Further advances in this subject area will require better research tools. Perhaps the most obvious need is for more advanced numerical and laboratory models of the dynamo process. The geodynamo couples the dynamics of the mantle, with its characteristically long time scales and slow viscous motion, to the dynamics of the core, with its characteristically short time scales and relatively fast, turbulent motion. Understanding the dynamics of each part separately is difficult enough, so it is no surprise that their interaction is a formidable challenge. Future models of the core will need far more capabilities to realistically simulate the full range of its dynamics and its actual physical properties, compared to what can be done at present. This will require significant advances in computational software and hardware, as well as experimental technology.

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10. Alternate Earths: Extra-Solar Planetary Interiors and their Surfaces

The Challenge

In the last two decades, astronomers have discovered more than 40350 planets around stars other than the Sun, of which more than 10 are now classified as 'super-Earths'. These discoveries enormously widen the scope for geodynamics, offering unprecedented opportunity to place the Earth and the other terrestrial planets in our solar system into a much broader cosmological context. For geodynamicists, the most important challenges are to connect the astronomical observables of these newly discovered objects with their interior structure, composition, and dynamics.

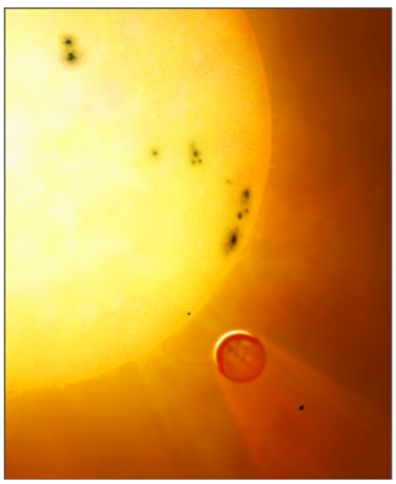

FIGURE 10.1: *Artist rendition of a close-in exoplanet with active mass loss, as proposed for CoRoT-7b. CoRoT-7b has a mass of 4.8 ± 0.8 MEarth (Queloz et al, 2009), a radius of 1.68 ± 0.09 REarth, and period of 0.85 days, a calculated effective temperature of 2000K and age of 1.9-2.3 Gyr (Leger et al, 2009). Considerable atmospheric loss is expected, given its proximity to the star; estimates indicate it might have lost about 2 times the mass of Earth already. This planet is likely terrestrial, implying that the evaporating atmosphere is composed of silicates (Valencia et al, 2009). With its high surface temperature, some form of near-surface magma ocean is expected (Shaefer and Fegley, 2009).*

Major Milestones

The realization that solid planets like our own exist outside our solar system began with the discovery of the first super-Earth a few years ago—certainly an important milestone accomplishment. Since then, observational and theoretical efforts to understand these objects have intensified. The super-Earth category includes newly discovered planets that are generally small enough to be mostly solid. Some of these are thought to be terrestrial (silicate and oxide composition) rather than icy. Additional detection discovery of hundreds of extra-solar terrestrial planets is anticipated within the next decade because they are relatively abundant in the cosmos and the instrumentational capability to detect them already exists. The frequency of these planets around sun-like stars in the HARPS (a planetary search program) catalogue is more than 30%. In particular, super-Earths are predicted to be relatively abundant in the cosmos, as many planets in the correct mass/size range have been observed from the ground already, despite the inherent limitations. sSpace missions now in operation (such as CoRoT and Kepler) as well as future missions have, or soon will have, the technical capability to measure key properties of Earth-like objects. For example, CoRoT reported in 2009 the first radius measurement of a super-Earth.

Major Questions

In light of the recent and anticipated discoveries, many fundamental questions can be posed, including:

- How similar are these planets to Earth?
- What is their range of internal structure and composition?
- How likely, or how frequently, do they evolve habitable surface environments?
- Is Earth a typical or atypical planet for its size, composition, and age?

Finding answers to these questions demands a multidisciplinary approach, based on real collaboration between geophysicists and astronomers. For example, to address the problem of habitability, we need to infer the state of the planet interior as well as its atmosphere and surface, all from a handful of astronomical observations.

A defining characteristic of the study of super-Earths is their wide range of possible compositions and states. The study of super-Earths seems almost unconstrained, with possible compositions, thermal states, evolution pathways, etc., that are yet to be conceived. In light of this, the approach to understanding these planets has to maintain a delicate balance between generality and specificity, always mindful of the need to make testable predictions, perhaps statistical ones, in order to take full advantage of the large number of detections expected. It is possible that such large numbers of new planets may simply lead to irreducible diversity. Alternatively, it may reveal biases we have inadvertently developed in the course of focusing on our home planet. In either case, it will certainly test the insight we have acquired in exploring the Earth and other solar system planets.

Observations

Relatively few types of observations are available for extra-solar planets. In many cases, the list includes the minimum mass, orbital period, and age of each object. For about 10% of these planets we also know their radii because their orbital geometry is favorable to observing the light diminution caused by the planet as it eclipses the star (i.e. a transiting planet). For a few optimal cases we have a spectrum that allows the inference of some compounds in their atmosphere.

With technological advancements in telescope design and implementation, as well as in data processing, the discovery pace is increasing. CoRoT, a French led space mission originally built to carry out astroseismology, was redirected to exoplanet discovery, and in February 2009 reported the first transiting super-Earth, CoRoT-7b. NASA's Kepler mission launched in March 2009 has the capability of discovering an Earth-mass planet in a one-year orbit around a sun-like star. The lower limit on the mass observable with radial velocity surveys is now just two times the mass of the Earth, and the James Webb space telescope, expected to launch in 2013, will be capable of measuring spectra of super-Earths.

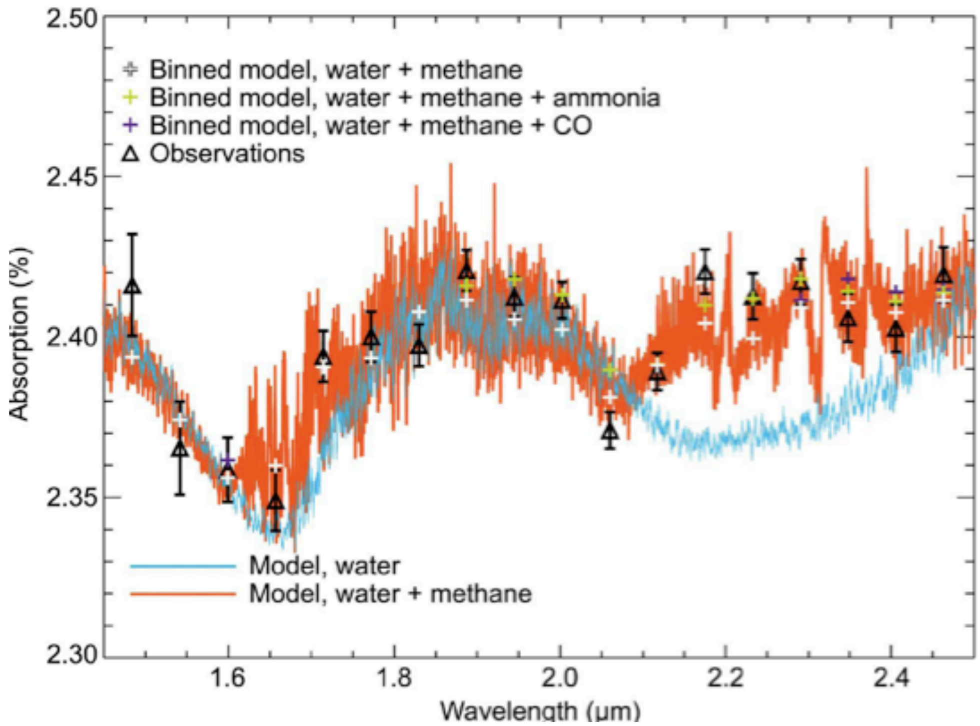

FIGURE 10.2: *Observed spectrum and model results for exoplanet HD 189733b. Swain et al. (2008) explained the observed spectrum by including water and methane in a model atmosphere. This is an example of the type of measurements and models expected for super-Earths in the next decade. The first atmospheric compound detected on an exoplanet was sodium on HD 209458b by Charbonneau et al (2002). Since then, other compounds in these two close-in planets stars have been identified (Vidal-Madjar et al. 2004, Deming et al. 2005, Tinetti et al. 2007, Swain et al. 2009).*

The amount of data expected for super-Earths over the next decade will rival that already obtained for the gaseous exoplanets. Initially, only minimum masses or radii will be known, but follow-up observations will provide the total mass and precise radius. In combination with orbital period and age, this will allow meaningful inferences about the composition. For transiting super-Earths in favorable configurations (i.e. orbiting close to a quiet star) crude spectra and in some cases radiation temperature can be gotten, allowing us to probe the atmosphere of these planets. Owing to the expected close relationship between the interior and the atmosphere of super-Earths, such spectra will be a powerful source of information about their interior dynamic state.

Structure and Composition

In the theoretical front, considerable progress has already been made in constraining the structure and composition of these planets. At least four different research groups have proposed mass-radius relationships for super-Earths. In spite of their differing model assumptions, equations of state, and temperature profiles, there is reasonable agreement on the most basic results.

By incorporating measurements of masses and radii, in combination with structure models, we hope to be able to distinguish planetary type (icy vs. terrestrial). Although many different compositional models can fit the limited data, much of the degeneracy can be removed in some cases. For example, given its close proximity to the star (at only 0.85 day orbit), and age (1.9-2.3 Gyr), CoRoT-7b is likely to be terrestrial in nature. Under these conditions, this planet is expected to have evaporating silicates and could have a partially molten surface.

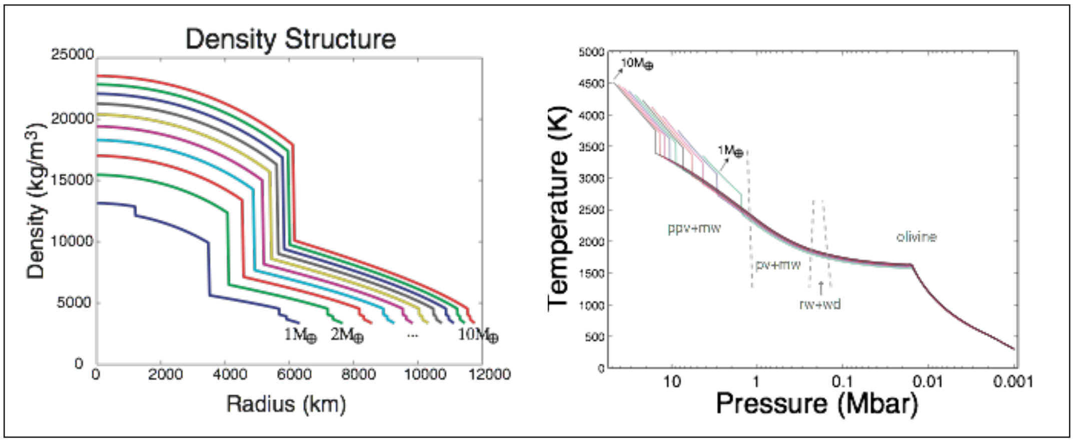

FIGURE 10.3: *Left: Density structure of terrestrial super-Earths (Valencia et al 2006). The mass-radius relationship follows a power-law with an exponent that ranges between 0.262-0.274 according to the different studies (Valencia et al, 2006; Fortney et al, 2007; Grasset et al, 2007; Seager et al, 2007). Right: Pressure-temperature regime of terrestrial super-Earths (Figure 1 in Valencia et al, 2009). By assumption, the mantles of these planets are mostly composed of the high-pressure silicate post-perovksite phase(Murakami, 2004). High-pressure experiments plan to explore the behavior of planetary material at super-Earth conditions (Molinard et al, 2009)*

The study of super-Earth's structure motivates further study of the behavior of planetary materials at high pressures and temperatures. Internal structure models show that the interior of these planets can reach pressures of 60 Mbars and temperatures of 104 K. Ab-initio calculations and experimental data are being extended to this pressure-temperature regime, to provide valid equations of state. One example is the study of the recently-discovered post-perovskite phase. In the Earth, this high-pressure silicate phase exists only in a small portion of the lowermost mantle, but it is expected to be a major component of super-Earths mantles. In addition, there might be even higher-pressure phases yet to be discovered that are relevant to the interiors of exo-Earths.

Thermal Evolution in Other Earths

A key issue in the evolution of extra-solar planetary interiors is whether or not plate tectonics is the dominant mechanism for internal heat transfer. The tectonic regime is critical, as it governs the atmosphere composition as well as the thermal evolution of the planet. Different groups have reached opposite conclusions on whether or not massive Earths are more or less likely to sustain plate tectonics. While there is agreement on the Byerlee criterion for plate boundary creation and the need for convection-induced stresses, there is much disagreement in other respects. For example, researchers use convective scaling laws based on internal heating, while others use scaling laws based on the surface heat flux. Although major disagreements are yet to be reconciled, these studies exemplify the range of geodynamical approaches for characterizing super-Earth tectonic processes.

The importance of the tectonic regime in these planets is two-fold: it directly bears on the atmospheric composition and the surface habitability. For example, the atmosphere of a planet with a stagnant lid is expected to be different than a planet with plate tectonics. In the latter case, there is greater exchange between the interior and the surface environment in terms of heat flux, volatiles, and other species. As super-Earth spectra become available, especially for abundant compounds such as H_2O, CO_2, O_3, it may be possible to infer the tectonic state of terrestrial super-Earths indirectly.

More research is needed to identify the connections between interior processes (such as plate tectonics, presence of a magnetic field, etc), with atmospheric composition. For example, given the role that plate tectonics plays in enabling the Carbonate-Silicate cycle in geological timescales, an adequate level of CO2 detected on a super-Earth might be indicative of the presence of a negative feedback cycle. Conversely, a detection of high levels of CO2 would be suggestive of a lack of plate tectonics. Approaching the subject in a statistical sense with dozens of observations will help better understand the physical processes governing plate tectonics, and thus contribute to explaining the different tectonic modes between Venus and Earth.

In addition, tectonics plays an important role in developing habitable surface conditions. On Earth, plate tectonics drives the rock cycle, constantly generating carbonates and other minerals that buffer the carbon dioxide content of the atmosphere. Subduction carries carbonates to the interior where the carbon is later released at back-arc volcanoes and mid-ocean ridges, thus closing the cycle. We know that the rock cycle is instrumental in regulating the surface temperature on geological timescales, providing a stable environment for life on Earth. A critical issue is whether a similar tectonically-driven rock cycle, and other factors such as a strong, stable internally-generated magnetic field, are essential for life on other planets.

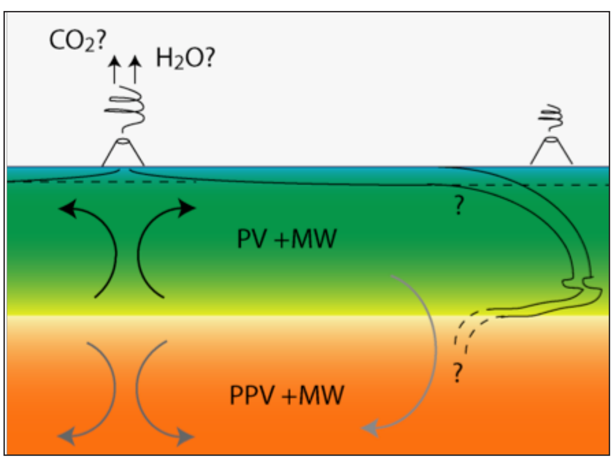

FIGURE 10.4: *Possible scenario for the mantle dynamics on super-Earths. Only the major silicate phases are depicted (PV: perovskite, PPV: post-perovskite and MW: magnesiowustite). It is unclear if plate tectonics is the primary mechanism by which massive Earth-analogs lose heat. Valencia et al. (2007) conclude that they are likely to have plate tectonics, whereas O'Neill and Lenardic (2007) conclude that episodic plate tectonics is more likely; see also Sleep (2009) and Tackley and Hein Van Heck (2009).*

If these planets have post-perovskite layers (Valencia et al. 2009), mantle convection might be layered. The mantle dynamics is expected to have a profound effect on the atmosphere composition. Anticipating that spectra will be determined for some super-Earths, modeling their atmospheres has already begun, including complex Earth-based atmospheric models (Kaltenegger et al, 2007) as well as simpler stellar-based models (Miller-Ricci et al, 2008).

The Frontier

The frontier in the study of extra-solar Earths lies at an interdisciplinary crossroad, where the traditional disciplines of astronomy, geophysics, atmospheric science, geochemistry, and cosmochemistry meet. Accordingly, efforts that enhance multidisciplinary interactions are vital and worthy of support. For geodynamicists in particular, the most immediate challenge is to develop novel ways to link the astronomical observables to interior dynamical processes. The long-term objective is a better understanding of the physical processes in a wide planetary context, that includes Earth, the terrestrial planets, as well as super-Earths. In terms of the atmosphere of exoplanets, the identification of major species has already been done for two Jupiter-like exoplanets: HD 209458b and HD 189733b. Similar types of observations are expected for the solid planets, increasing the need for innovative atmosphere models. Better resolution of planetary material behavior at high pressures and temperatures is also crucial. And, in light of the diversity we have already seen in exoplanets, a much wider range of possible compositions and internal dynamic styles needs to be examined.

Further Reading

Super Earths: Observations

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Super Earths: Dynamics

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Community and Funding Organizations

Research in geodynamics in the U.S. benefits from a variety of organizational structures and support agencies. The American Geophysical Union (AGU) has traditionally served as the primary U.S. organization for dissemination of knowledge in this subject area, through its annual meetings, journals, and specialized conferences. The Tectonophysics Section and the Deep Interior (DI) Focus Group of the AGU have been particularly active in this regard, serving as multidisciplinary venues for integrating geodynamic research into the broader context of Earth dynamics. Internationally, the SEDI (Studies of Earth's Deep Interior) committee within the IUGG serves a similar function, holding a bi-annual meeting where deep Earth dynamics studies are prominent. The Gordon Research Conference (GRC) sponsors a summer-time geophysics conference every second year, with a focus alternating between the shallower and deeper parts of Earth's interior.

In terms of funding agencies, several National Science Foundation (NSF) programs within the Geosciences Directorate have been particularly comprehensive in the development of this subject. Two of these are the NSF Geophysics Program and the NSF Cooperative Studies of Earth's Deep Interior (CSEDI) Program, both of these within the EAR Division. Other parts of EAR, including Continental Dynamics (CD), Tectonics, and also Instrumentation and Facilities (IF) provide support for geodynamics, as well as interdisciplinary research that involves geodynamics. In regard to computational support, the (NSF) funded project Computational Infrastructure for Geodynamics (CIG) has led the way in developing and supporting standardized, open source numerical codes for geodynamics. CIG is committed to develop and support standardized, benchmarked, documented geodynamic codes in mantle and core dynamics, computational seismology, melt physics, and short-term and long-term crustal dynamics, the computational tools that will be needed to address the challenges described in this document. Several programs within the National Aeronautical and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) also support geodynamics research.

In terms of graduate training, the NSF-funded Center for Interdisciplinary Deep Earth Research (CIDER) program offers annual educational workshops on diverse topics, all of which are related to geodynamics. This organization is particularly forward-looking in its emphasis on interdisciplinary training of future U.S. researchers.

Education and Training Requirements

Very heavy demands will be placed on the next generation of researchers in this subject. As geodynamics becomes more fully integrated into the science of the Earth system, we anticipate that the traditional discipline boundaries will increasingly come to be seen as barriers to future progress. What will emerge in their place remains for the future, but we expect that successful research in this arena will require training in a highly diverse set of knowledge and skills, which includes traditional geophysics, but also includes several new fundamental and applied subjects.

In order for U.S. students to have an impact on the grand challenge caliber problems in geodynamics, they will need a broader technical background, with expertise in at least several of the following fields, and just as importantly, some proficiency in most if not all of the others:

- Advanced continuum physics (not simply introductory-level geodynamics)
- Materials science
- Mineral physics
- Fluid dynamics
- Thermodynamics and statistical mechanics
- Inverse theory
- Numerical methods
- High-performance computing

In addition, it will be imperative that students in geodynamics have a working familiarity with the fundamentals in allied disciplines such as seismology, the environmental sciences (including the ocean and atmosphere), and geology.

Lastly, further progress in geodynamics will almost certainly depend on the researcher's ability to process and interpret data sets that are immensely larger than we presently deal with. Accordingly, we anticipate that specialized training will be required to properly exploit the vast amounts of data that are expected to come from observational and computational projects in the future.

Facilities

Computational

Large-scale computing will play an increasingly important role in future Earth Science research in general, and in geodynamics in particular. In geodynamics, large-scale computing involves capability and capacity, both of which are vital to progress.

Capability entails code development and basic parameter exploration. Experience shows that these steps are best done at a fairly local level, within an individual research group or between a small group of researchers at different institutions, collaborating in the context of a focused infrastructure like CIG (Computational Infrastructure for Geodynamics). The computational hardware resources needed for these steps typically consist of small or mid-sized clusters. What is more important for these steps are the intellectual resources; we have learned that enhanced capability depends on fusing into geodynamics the knowledge and experience of software developments from computational science and allied disciplines.

The next step, capacity computing, involves the application of stable, well-calibrated codes to very large problems. For the most part, approaching realistic conditions and parameters in geodynamic computations is linked to broadening the range of spatial and temporal scales that a particular geodynamic model simulates, as well as incorporating additional physical and chemical processes over these scales. In regard to capacity, Petascale machines are logical tools of choice now on the horizon, as they open the possibility of exploring geodynamic phenomena over a much more extensive range of spatial and temporal scales than can be done at the local level. Another recent development in hardware with future promise is the emerging GPU (Graphical Processor Unit) technology, which offers the prospect of many-fold increases in compute power at far lower energy costs.

We emphasize that, while Petascale and GPU computing have potential to transform geodynamics modeling, it will first be necessary to develop software that scales well on computers with tens of thousands of processors, is capable of handling the extreme ill-conditioning that characterizes many geodynamic problems, or in the case of GPU computing, is capable of running in this new environment. Because of these wide-ranging software and hardware challenges in geodynamics, there is abundant opportunity for creating mutually beneficial collaborations with private industry and governmental agencies.

Experimental

Laboratory experiments have traditionally played a relatively minor but nevertheless seminal role in geodynamics research. Many of the backbone concepts in numerical models that are now widely applied to geodynamics processes were actually first demonstrated experimentally, using laboratory analog solids and fluids. Because of their "hands-on" nature, laboratory experiments also serve as a vehicle for recruiting students into geodynamics, particularly students from outside of the traditional geophysics curricula. As geodynamics broadens its scope to encompass greater ranges of spatial and temporal scales and wider process interactions, inventive experiments will be an important component for progress. Accordingly, there is a need to create an infrastructure for laboratory geodynamics experimentation in the U.S., to take advantage of the technical developments in experimental design, data acquisition, and data processing that have already revolutionized parts of private industry.