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REVIEW

Mantle Convection and Plate Tectonics: Toward an Integrated Physical and Chemical Theory

Paul J. Tackley

Plate tectonics and convection of the solid, rocky mantle are responsible for transporting heat out of Earth. However, the physics of plate tectonics is poorly understood; other planets do not exhibit it. Recent seismic evidence for convection and mixing throughout the mantle seems at odds with the chemical composition of erupted magmas requiring the presence of several chemically distinct reservoirs within the mantle. There has been rapid progress on these two problems, with the emergence of the first self-consistent models of plate tectonics and mantle convection, along with new geochemical models that may be consistent with seismic and dynamical constraints on mantle structure.

Subsidiary (1) convection of the rocky, 2900-km-thick mantle of Earth (2) is the driving mechanism for plate tectonics and associated geological activity on the surface of our planet, including continental drift, earthquakes, volcanoes, and mountain building (3). Mantle convection and plate tectonics are one system, because oceanic plates are the cold upper thermal boundary layer of the convection. The slow motion of plates and the mantle is powered by radiogenic heating and by the slow cooling of our planet over its 4.5-billion-year history (4). Mantle convection and plate tectonics provide the central framework linking the subdisciplines of solid Earth science, including geochemistry, seismology, mineral physics, geodesy, tectonics, and geology. A successful model must thus satisfy constraints from all of these fields. For example, seismic waves provide a direct probe of structures inside Earth, chemical analyses of erupted lavas and other volcanic products give information about different compositions that exist in the mantle, and laboratory experiments determine the properties and deformation mechanisms of rocks at the high pressures (≤ 136 GPa) and temperatures (≤ 4000 K) of Earth's mantle.

Despite three decades of research, some first-order questions regarding the plate-mantle system remain largely unresolved.

The first of these is why Earth developed plate tectonics at all, given that other terrestrial planets such as Mars and Venus do not currently exhibit this behavior (3). The problem is complex because rocks exhibit many different deformation mechanisms, ranging from brittle failure to viscous creep, depending on the pressure, temperature, differential stress, and past history of deformation (5, 6), and many of these mechanisms are not well quantified. The second major question is how the differing chemical compositions of erupted magmas, which require several chemically distinct reservoirs within the mantle (7), can be reconciled with other observational and dynamical constraints favoring whole-mantle convection (8), which should mix chemical heterogeneities.

There has been substantial recent progress toward resolving these two issues, such that a self-consistent physical and chemical model capable of integrating plate tectonics, geochemical observations, and other constraints may be possible within the next decade. This review focuses on these two issues. However, there has also been important progress in other areas, notably (i) understanding how the present state of the mantle, as imaged by seismic tomography, is related to the recent (~ 140 million year) history of plate motions and recent geological events (9–11); (ii) basic mantle dynamics, particularly the influence of non-Newtonian rheology (12–14); and

(iii) plume dynamics, including formation from a hot thermal boundary layer (15) and interaction with plates (16, 17).

The Plate Problem

Plate tectonics does not arise from convection by viscous creep with temperature-dependent viscosity. Instead, a rigid lid is formed with convection taking place beneath it. The other terrestrial planets display a rigid lid, although plate tectonics may have existed in the past on Mars (18) or Venus (19), with Venus perhaps fluctuating between plate tectonics and a rigid lid (20). A rigid lid forms because the temperature drops from 1600 K (mantle) to 300 K (surface) over the upper thermal boundary layer, and the thermally activated processes responsible for mantle deformation (2) become many orders of magnitude slower as temperature decreases (14). Our understanding of rigid lid convection has been greatly refined by several recent studies (13, 21, 22).

Earth does not have a rigid lid. Instead, convection reaches the surface, and oceanic plates are the upper thermal boundary layer participating in the convective motion (23). Additional deformation mechanism(s) are responsible for breaking the stiff outer lid into strong plates separated by weak boundaries (24, 25). Field observations and laboratory experiments give guidance as to these mechanisms (5, 6). Faults form by brittle failure near the surface, but increasing pressure (hence friction) with depth limits faults to the upper ~ 15 km of the plates, which are some tens of kilometers thick. Below ~ 15 km, deformation is probably accommodated by distributed microcracks (5). Laboratory experiments indicate that the yield strength of rocks is hundreds of megapascals and is weakly dependent on pressure (26). Plastic flow, by lattice processes such as dislocation glide, occurs at higher pressures and stresses (6). Thermally activated viscous creep (2, 14) takes over at higher mantle temperatures and greater depths.

In addition to the above mechanisms,

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strain weakening may occur. Field observations of shear zones indicate several strain-weakening mechanisms, including dynamic recrystallization (27), reactions with volatiles (28), and heat production through viscous dissipation (27). Because most new plate boundaries on Earth form by activation or reactivation of preexisting zones of weakness (29), deformation history is also important.

Self-Consistent Plate-Mantle Models

Recently, some of these deformation and weakening mechanisms have been incorporated into numerical models of mantle convection, and the first generation of self-consistent plate-mantle models is emerging (24, 25). Previous simulations generally modeled only temperature-dependent viscous creep, requiring plates to be inserted by hand, often using prescribed kinematic rules (9, 30).

Yielding of the lithosphere by distributed

brittle failure gives a rudimentary approximation of plate tectonics in two-dimensional (2D) numerical models (31). Weak plate boundaries form above downwellings because their negative buoyancy causes a concentration in stress, whereas spreading centers are weak because the plates are thin. The form of convection depends on the yield strength of the material. Rigid lid behavior occurs at high yield strength, episodic plate tectonics occurs at intermediate yield strength, and steadily evolving plate tectonics occurs at low yield strength.

Three-dimensional (3D) geometry introduces fundamental differences because of the presence of transform (strike-slip) boundaries and associated toroidal motion (25, 32). Because there are no buoyancy forces available to weaken transform boundaries, strain weakening is necessary for their formation. Strain weakening and healing associated with viscous dissipation (33) or void creation and

volatile ingestion (28) lead to the formation of weak, focused transform boundaries in steady-state 2D models representing the lithosphere, and in steady-state 3D models with buoyancy sources driving flow in a thin lithospheric sheet (34, 35). In contrast, power law (34) or plastic yielding (35) rheologies do not lead to localized transform boundaries.

Plate-like behavior was recently obtained in 3D time-dependent models that included only the finite yield strength of rock, with no strain weakening (36–38). The first such model displayed only localized (in space and time) plate-like behavior (36). A more thorough exploration of parameter space found continuous, smoothly evolving plate-like behavior (37), with trends similar to those in previous 2D experiments (31). A low-viscosity region underneath the plates [as observed in Earth (8)] lubricates spreading centers, making them more localized and less episod-

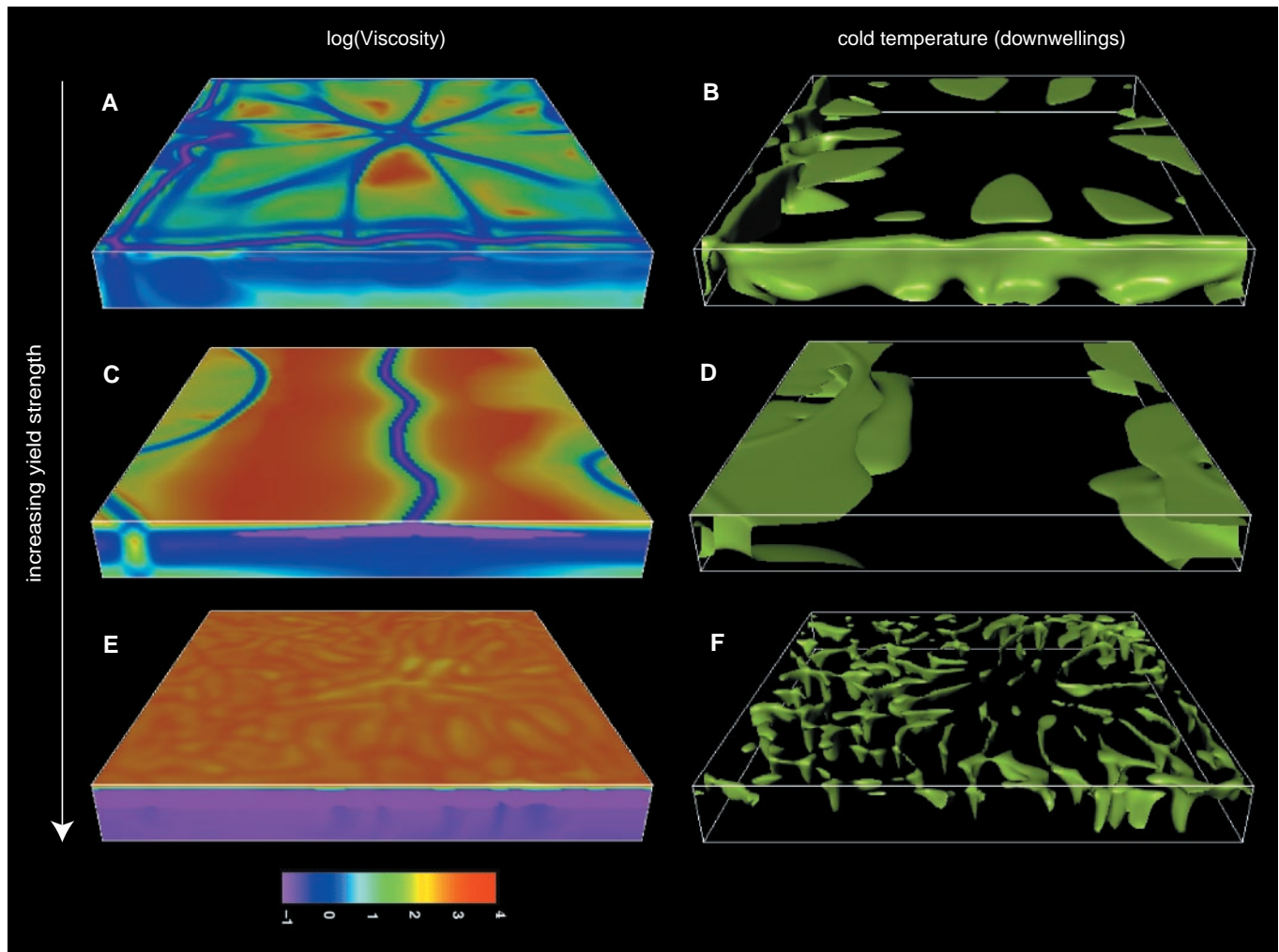


Fig. 1. Numerical simulations of mantle convection with self-consistently generated plate tectonics [from (38)]. The rheological model incorporates temperature-dependent viscosity varying by up to five orders of magnitude, a constant (with depth) yield stress, and a factor of 10 viscosity reduction when the temperature reaches the solidus. The left column shows the logarithm of viscosity relative to a reference mantle value; red corresponds to the strongest material and purple corresponds to the

weakest material. The right column shows cold downwellings (where the temperature is 250 K colder than the horizontal average). System behavior depends critically on the yield strength: With low yield strength (A and B), plate-like surface motion is observed but plates are weak. With intermediate yield strength (C and D), plate-like behavior is observed with strong plates and weak boundaries. With high yield strength (E and F), rigid lid behavior is observed.

ic (38) (Fig. 1). These simulations do not develop pure transform boundaries. Instead, every boundary has a mixture of divergence and transform motion. Although these advances are encouraging, the plates are not Earth-like. They have unrealistically broad plate boundaries, subduction that is symmetric (whereas on Earth one plate slides under the other), and no pure transform boundaries; moreover, they require lithospheric yield strengths as low as ~150 MPa for plate-like behavior, compared with laboratory values of ~500 MPa or more (5, 26).

Some important advances have come through regional or local models. Shear zones through the lithosphere can form in only ~50,000 years by the rapid release of elastic energy (39); recrystallization due to deformation can lead to shear zone formation under conditions of high (10 to 100 MPa) stress and lithospheric cooling (27, 40) aided by viscous dissipation (41) [which is helped by heat trapping due to decreased thermal conductivity in hot shear zones (42)]; and localization may occur through volatile infiltration and reaction (43). Extremely high resolution is necessary to represent such small-scale localization in global numerical models.

Continents

Many studies (44–52) have focused on continental plate regions, without being concerned about how oceanic plates form. Continents cover nearly one-third of Earth's surface and consist of buoyant material, ≤300 km thick, that remains at Earth's surface for billions of years. Assemblages called supercontinents may have formed several times during Earth's history, perhaps cyclically.

Upwelling mantle flow naturally develops underneath a large continent (44), causing tensile stresses of order 100 MPa that may break it up (45, 46). A combination of broad, hot material under the continent and subduction forces at its edges generates sufficient stresses to break up a continent in ~200 million years (47), contradicting previous notions that focused upwelling plumes are required for continental breakup.

Heat flow from the mantle into cratons (the old, stable parts of continents) is approximately constant regardless of the craton's age (48), and heat flow through cratons more than 2.5 billion years ago was similar to that at present, whereas the heat flow out of Earth was much higher because of its steady cooling (49). When continents are incorporated as deformable, buoyant material into a convecting mantle, the above observations arise naturally (48–50).

Buoyancy alone is insufficient to stabilize 200- to 300-km-thick cratons for billions of years. A viscosity ~1000 times the normal upper mantle viscosity of 10²⁰ to 10²¹ Pa·s is also necessary (50–52).

Geochemical Reservoirs

Plate-mantle dynamics results in competing chemical differentiation and mixing. Partial melting of the mantle at mid-ocean ridge spreading centers and other magmatic environments causes differentiation. The differentiated products can reenter the mantle at subduction zones (23). Mantle convection mixes and homogenizes chemical heterogeneities.

Magmatic products erupted at different settings (discussed below) are different in their concentrations of incompatible trace elements (53) and are assumed to be derived from different regions of the mantle (7). Crustal rocks formed at mid-ocean ridges (mid-ocean ridge basalts or MORB), assumed to be derived from passively upwelling shallow mantle, are fairly homogeneous in composition and derived from mantle rocks that are depleted in incompatible trace elements (54). Rocks formed at ocean islands (ocean island basalts or OIB), which can occur in chains like the Hawaiian chain and are thought to be related to upwelling plumes from a deep hot boundary layer (8), are less depleted than MORB and have variable compositions that are interpreted to result from mixing between the depleted MORB mantle (DMM) and

three other reservoirs. These reservoirs have been radiometrically dated as 1 to 2 billion years old—equivalent to several “overturns” of mantle convection (4), but less than the age of Earth. Thus, they are not primordial but were probably formed by the recycling of former oceanic or continental crust (and possibly continental lithosphere). Some OIB display an anomalously high ratio of ³He/⁴He. ³He dates from Earth's formation, whereas ⁴He is continuously produced by the radioactive decay of U and Th. Thus, a high ³He/⁴He ratio is commonly interpreted as evidence for an additional, primitive reservoir that has remained separate since the earliest Earth. The inferred concentrations of heat-producing elements in DMM are insufficient to explain Earth's heat flux; these missing heat-producing elements are perhaps concentrated in one of the other reservoirs.

Mantle Layering at 660 Kilometers?

Many geochemists have favored models in which the mantle is chemically and dynamicaly layered, with the upper mantle (55) being DMM and the lower mantle being primitive (Fig. 2A). However, other observational and dynamical constraints prohibit total convective

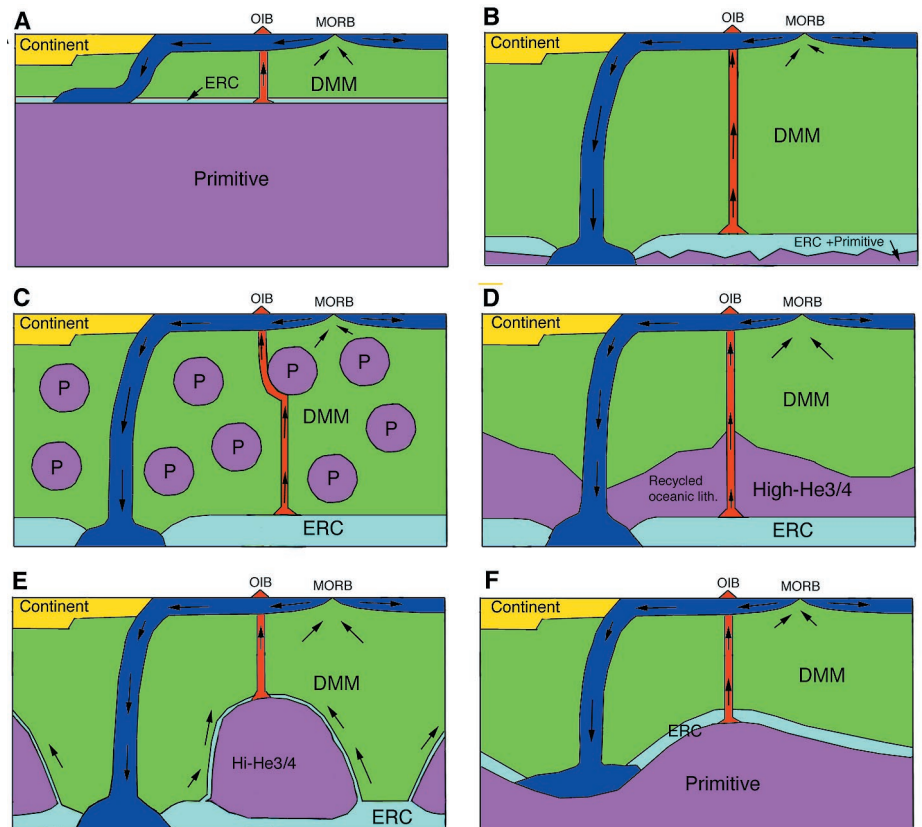


Fig. 2. Some possible locations of mantle reservoirs and relationship to mantle dynamics. Convective features: blue, oceanic plates/slabs; red, hot plumes. Geochemical reservoirs: dark green, DMM; purple, high ³He/⁴He (“primitive”); light green, enriched recycled crust (ERC). (A) Typical geochemical model layered at 660 km depth (7). (B) Typical geodynamical model: homogeneous except for some mixture of ERC and primitive material at the base. (C) Primitive blob model (71) with added ERC layer. (D) Complete recycling model (83, 84). (E) Primitive piles model [developed from (85)]. (F) Deep primitive layer (86).

layering at 660 km depth (8), leading geodynamacists to favor whole-mantle convection (Fig. 2B). Arguments against layering have been reinforced by high-resolution global models of 3D mantle velocity structure obtained using seismic tomography (56–58), which indicate recently subducted downgoing oceanic plates (“slabs”) in the lower mantle (Fig. 3). Supporting this interpretation are mantle convection models in which plate motions for the last 140 million years are imposed as a surface boundary condition (9); these models display volumetric structure resembling the seismically imaged structure. In many places, the slabs appear to temporarily flatten out above the 660-km discontinuity before descending into the lower mantle, as expected from the actions of a major mineralogical phase transition at this depth (59–62).

Homogenization by Mixing

Even with whole-mantle convection, early models (63) suggested that the lower mantle could retain a primitive composition if its viscosity is ~ 100 times the upper mantle viscosity. However, recent calculations (64, 65) at an Earth-like convective vigor (4) find instead that the lower mantle becomes well

mixed and outgassed over billions of years, regardless of the presence of inhibiting mechanisms such as higher viscosity, temperature-dependent viscosity, and an endothermic phase transition at 660 km depth (65).

Plate tectonics introduces a toroidal component to mantle flow, which is not present in 2D geometry (32). Toroidal flow can cause chaotic mixing even in steady-state 3D flows (66), resulting in efficient mixing (67), although unmixed “islands” can occur within efficiently mixed regions. For plausible present-day 3D mantle flow and plate velocities, most regions of the mantle exhibit corkscrew-like particle motions that may be associated with chaotic mixing (68). These results suggest that mixing in Earth’s mantle is expected to be quite efficient, with unmixed primitive regions unlikely to survive over geological time.

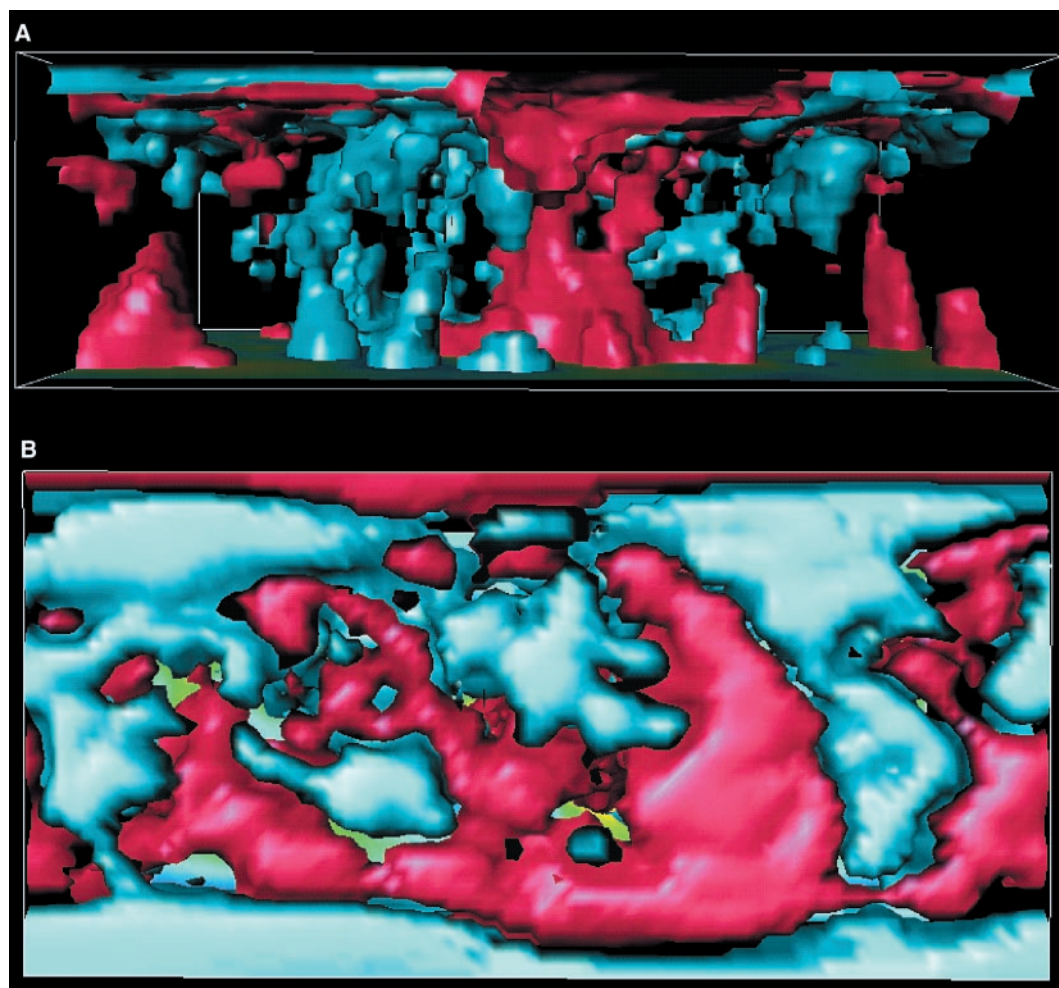
Mixing efficiency is reduced by lateral viscosity variations caused by non-Newtonian rheology (14, 69), or high-viscosity blobs. Blobs with a viscosity 10 to 100 times that of normal mantle deform slowly enough to remain unmixed after billions of years (70). Primitive material existing in the form of such blobs could constitute 35 to 65% of

the total mantle volume (71). The blobs would be hidden from mid-ocean ridge spreading centers but sampled by plumes (Fig. 2C). A problem is the difficulty in balancing thermal and compositional buoyancy. The blobs should either float to the top or sink to the bottom, forming a layer.

Deep Chemical Layering?

With layering at 660 km depth and the long-term survival of volumetric heterogeneities disfavored, a remaining possibility is layering deeper in the mantle. Indeed, there is much observational evidence to suggest chemical heterogeneity in the deep mantle: (i) D'' , a 200- to 300-km-thick region observed in some areas at the base of the mantle, displays seismic scattering, heterogeneity, and anisotropy (72), and a chemical origin is plausible, although not certain (73, 74). (ii) Two huge “megaplumes” under Africa and the Pacific are observed in seismic tomographic models (Fig. 3). Several characteristics of these suggest a partly chemical origin: They are sharp-sided (75), their seismic velocity anomalies are too large to be purely thermal (76), it is difficult to obtain such structures in thermal convection calculations (77), and inversions

Fig. 3. Structure in the mantle, as imaged by seismic tomographic model SB4L18 (58). Blue isocontours show where the shear wave velocity is 0.6% higher than normal (“cold” material), and red isocontours show where the shear wave velocity is 1% lower than normal (“hot” material). (A) Looking from the south, with the CMB at the bottom of the image and Earth’s surface at the top of the image. Downwelling former oceanic plates (blue) appear to sink to the CMB in most areas. Two large megaplumes (red) are observed underneath Africa (left of image) and the Pacific (center of image). (B) Looking down from above, the pattern of continents and oceans is clearly visible.



of normal mode-splitting functions for 3D mantle density structure (78) indicate that they are anomalously dense, opposite to the density anomaly of hot thermal upwellings. (iii) Seismic *P*-wave and *S*-wave velocity variations are decorrelated or anticorrelated deep in the mantle (79, 80), inconsistent with a thermal origin. (iv) Seismic tomographic models change their statistical character [e.g., lateral spectrum or radial correlation function (81)] 1000 to 1500 km above the core-mantle boundary (CMB). (v) Some seismic tomographic models (56) suggest that most slabs stop ~1200 km above the CMB, although other models (e.g., Fig. 3) show deep slab penetration.

It is important to ascertain what form a deep, dense layer could take, and how this would explain the geochemical and seismological observations. Two aspects must be addressed: the dynamical feasibility of crustal recycling for generating the 1- to 2-billion-year-old reservoirs, and the origin of the high-³He/⁴He (primitive) reservoir. The dynamical feasibility of crustal recycling was demonstrated using a convection model (82) in which one of the enriched reservoirs was generated by partial separation of subducted oceanic crust into a layer at the base of the mantle.

Two classes of models have recently been proposed for the high-³He/⁴He reservoir. The first is an accumulation or layer of former oceanic lithosphere (83, 84). This would have a high ³He/⁴He ratio because partial melting at mid-ocean ridges causes rocks to lose almost all of their U and Th, which produce ⁴He over geologic time, causing ³He/⁴He to decrease. Thus, ³He/⁴He is frozen at the higher value present when the rocks first became oceanic lithosphere. Geochemical models have recently demonstrated that combined lithospheric and crustal recycling can explain the high-³He/⁴He reservoir and the 1- to 2-billion-year-old reservoirs (83, 84) (Fig. 2D). The missing heat-producing elements are concentrated in the recycled crust layer. The dynamical feasibility of this model with respect to convective mixing remains to be demonstrated.

The second proposal for the high-³He/⁴He reservoir is a primitive, primordial layer (containing the missing heat-producing elements), like traditional geochemical models (Fig. 2A) but with a deeper boundary. Two studies have focused on different amounts of primitive material (85, 86). In the first study (85), it was proposed that primitive material forms a discontinuous layer (Fig. 2E) consisting of two piles corresponding to the two megaplumes (Fig. 3). The piles would be hot as a result of radiogenic heating, with thermal upwellings arising from their tops, thus explaining the distribution of hot spots (8) and the topography of southern Africa (87). This model fits most of

the seismic observations because it corresponds to structures that are directly imaged. However, the volume of the piles is rather small to satisfy geochemical constraints (7), and the CMB would be depressed under the piles, contradicting geodetic constraints (88). The second study (86) proposed a global, undulating layer of average thickness 1300 km (but varying by ~1000 km) and constituting ~30% of mantle mass (Fig. 2F), overlain by a recycled crust layer. This model fits current geochemical constraints and some seismic constraints, particularly the stopping of slabs ~1300 km above the CMB in some seismic tomographic models (89). However, it is necessary to explain why such a layer is invisible seismically, because the undulating boundary and the recycled layer above it should generate a considerable amount of volumetric seismic heterogeneity at mid-mantle depths. One possibility is that the effects of thermal and compositional variations on seismic velocities cancel out. The remaining seismic signature would then be an internal thermal boundary layer ~200 km thick overlain by the recycled crust layer, the seismic signature of which is undetermined.

Dynamical aspects of a deep, dense layer were recently investigated using laboratory experiments (90). At density contrasts of ~1%, hot domes are observed to oscillate vertically through the whole mantle while thin tubular plumes rise from their upper surfaces. This doming regime is a transient phase preceded by stable layering and followed by large-scale mixing. Possibly, Earth is currently in this regime, thereby explaining the long-term survival of a primitive reservoir while giving small present-day density heterogeneities.

Future Directions

The advances discussed in this review are quite preliminary: The new geochemical models are untested by a full range of dynamical and observational constraints, whereas the plate tectonics models are not realistic and include only a simplification of rock rheology. The preferred working model is that obtained by straightforwardly interpreting seismic tomography (Fig. 3): Slabs penetrate to the CMB, and the high-³He/⁴He reservoir is contained in two large megaplumes (Fig. 2E). In a uniformitarianist view, this reservoir would be recycled oceanic lithosphere (Fig. 2D). The plate-mantle system is intrinsically time-dependent and possibly episodic, and if these domes (90) were currently rising, this could induce positive CMB and surface topography consistent with observations (88). In the future, this and other thermochemical plate-mantle models must be thoroughly tested, with the understanding that an Earth-like model of chemical cycles and mantle mixing requires an Earth-like plate tectonic regime.

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REVIEW

Earth's Core and the Geodynamo

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Earth's magnetic field is generated by fluid motion in the liquid iron core. Details of how this occurs are now emerging from numerical simulations that achieve a self-sustaining magnetic field. Early results predict a dominant dipole field outside the core, and some models even reproduce magnetic reversals. The simulations also show how different patterns of flow can produce similar external fields. Efforts to distinguish between the various possibilities appeal to observations of the time-dependent behavior of the field. Important constraints will come from geological records of the magnetic field in the past.

Earth evolved into a layered body early in its history. Molten metal (mainly iron) descended to form the present-day core, while silicates and oxides were confined to a thick shell called the mantle. The innermost part of the core is now solid, whereas the outer portion is liquid (Fig. 1). The viscosity of the liquid outer core is comparable to that of water (1), which permits vigorous convection as the core cools. Fluid velocities on the order of 10 km per year, (2) are sufficiently rapid to sustain Earth's magnetic field through a mechanism known as the geodynamo.

Planetary rotation promotes the types of flows that are needed to generate the magnetic field. However, the resulting magnetic field exerts a strong feedback on convection, which complicates quantitative predictions of the field generation. An important advance in recent years is the development of numerical simulations that achieve self-sustaining dynamo action (3–5). Computational limitations prevent these simulations from reaching Earth-like conditions, but the models obtained so far have external magnetic fields that are similar to Earth's field (Fig. 2).

The operation of the geodynamo depends on the internal evolution of the planet because convection in the core is linked to the rate of cooling. The transport of heat through the man-

tle is crucial for powering the geodynamo, and even the existence of plate tectonics at the surface is an important factor. Interactions between the core and the mantle are expected, though it is unclear how these interactions are expressed in the magnetic field. Persistence of the magnetic field over most of Earth's history implies continual cooling and convection in the core. By contrast, the absence of magnetic fields in our nearest planetary neighbors (6) indicates that other thermal histories are possible. As we gain a better understanding of the geodynamo and the dynamics of the core, new perspectives about the processes that drive the internal evolution of Earth are expected to emerge (7).

Origin and Evolution of the Core

The initial supply of energy for the geodynamo is established by the state of the core at the time of its formation (8). Subsequent cooling delivers this energy to the geodynamo over geological time. Although a detailed reconstruction of the formation and evolution of the core is not possible, we can identify some of the processes that must have occurred. It is generally believed that the core began forming soon after Earth

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