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Mantle Dynamics

7.01 Mantle Dynamics Past, Present and Future: An Introduction and Overview*

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Contents

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7.01.1 Introduction

Much of what we refer to as geology, or more accurately geological activity on Earth, is due to the simple act of our planet cooling to space. What allows this activity to persist over the lifetime of the solar system is that the major and most massive portion of the planet, namely the mantle, is so large, moves so slowly and cools so gradually that it sets the pace of cooling for the whole Earth. If the Earth's other components, such as the crust and core, were allowed to lose heat on their own, their small size or facile motion would have allowed them to cool rapidly and their activity would have ceased aeons ago.

For this reason the study of the dynamics of the mantle, both its evolution and circulation, is critical to our understanding of how the entire planet functions. Processes from plate tectonics and crustal evolution to core freezing and hence the geodynamo are governed, and in many ways driven, by the cooling of the mantle and the attendant phenomenon of mantle convection, wherein hot buoyant material rises and cold heavy material sinks.

7.01.2 A Historical Perspective on Mantle Dynamics

To some extent the development of the field of mantle dynamics is most closely linked with the history of theories of continental drift and plate tectonics. Although mantle convection was invoked to provide a driving mechanism for continent (or plate) motions, the hypothesis that the mantle flows and circulates predates even that of continental drift [see Schubert et al., 2001, Ch.1]. As discussed recently by England et al. [2007], John Perry used the notion of mantle convection in 1895 to refute the estimate for the age of the Earth given by his former mentor William Thomson (Lord Kelvin). However, a great deal of progress on understanding mantle convection also comes, obviously, from the general study of the physics of thermal convection, not specifically applied to the mantle.

Histories of plate tectonics (or continental drift) are in abundance [e.g., Menard, 1986; Hallam, 1987] and the recent text on mantle dynamics by Schubert et al. [2001] gives an excellent summary of the history of the development of mantle convection theory in conjunction with plate tectonics. However, the historical context and personalities associated with some of the steps in this development are important to understand in terms of how the field evolved, and to some extent how science in general has been done and is done now. Thus rather than merely repeat other historical summaries here, I will instead focus on the contributions (pertaining primarily to mantle convection) and professional and personal histories of some of the leading names in the development of the theories of thermal convection and mantle dynamics. Roughly keeping with the structure of this volume, I will concentrate on the origins of the physics, theory, and systematic experiments of convection by visiting Benjamin Thompson (Count Rumford), John William Strutt (Lord Rayleigh), and Henri Claude Bénard. This will be followed by reviewing the lives of some of the pioneers of the quantitative analysis of mantle convection as a driving force of "continental drift" namely Arthur Holmes, Anton Hales and Chaim Pekeris, and then two leading proponents of convection and its association with the modern theory of seafloor spreading, subduction and plate tectonics, Harry Hammond Hess and Stanly Keith Runcorn. Apart from hopefully providing an in depth perspective on the origins of the science of mantle convection, this survey also reveals the rather fascinating historical ties many of these famous characters had with one another; for example that Rayleigh had become a Professor in the institution that Rumford established, that Holmes had studied under Rayleigh's son, and that Chaim Pekeris was intimately involved with the birth of the state of Israel that Rayleigh's brother-in-law Arthur Balfour helped create.

7.01.2.1 Benjamin Thompson, Count Rumford (1753-1814)

Benjamin Thompson is perhaps one of the more colorful and complex characters in the history of science. He was simultaneously a brilliant observationalist, an egotistical opportunist, and a dedicated social reformer and champion of the poor. His role as spy against the rebelling American colonies on behalf of the British gives him a dubious role in American (although not European) history in that one of the fathers of thermodynamics also played a role not unlike that of Benedict Arnold.

Rumford is primarily known for his work on the theory of heat as motion – leading eventually to the kinetic theory and thermodynamics – and for working to debunk the caloric theory of heat. Histories of convection will often note that Rumford is credited as possibly being the first to observe convection; in fact, the study of the mass transport of heat was a significant part of his overall body of work [Brown, 1967] and he wrote an important article on convection in 1797, although the use of the word "convection" was not coined until much later, by Prout in 1834 [see Schubert et al., 2001].

Benjamin Thompson was born in Woburn Massachusetts in 1753 to a line of Thompsons that can be traced back to a James Thompson who arrived 10 years after the landing of the Mayflower (1620), along with with eventual Massachusetts Governor John Winthrop. Thompson's father and grandfather were reasonably wealthy farmers, but his father died young when Benjamin was less than two years old. The family farm was inherited by Benjamin's uncle who appears to have treated his nephew well with a significant income, a portion of land, and a high-quality education. As with all the subjects of our histories here, Thompson was a brilliant student, displaying talents in mechanics and natural philosophy; however he was also known for being a somewhat spoiled child at his family's farm.

Thompson left school at age 13 for an apprenticeship in retail, but continued his studies independently in engineering, mathematics, medicine, experimental philosophy, along with French, fencing, music and draftsmanship. He also carried out independent experiments in science, including astronomy, engineering, anatomy, and nearly electrocuted himself trying to repeat Benjamin Franklin's experiments on thunderstorm electrification.

At age 18, Thompson set out to generate much needed income and turned to tutoring the children of local wealthy families, which led to his being invited by the Reverend Timothy Walker of Concord, New Hampshire to run a school in his village. Concord was originally known as Rumford and it is from this town that Thompson was to derive his name upon being ennobled. Thompson courted The Reverend Walker's daughter Sarah, who had earlier married a

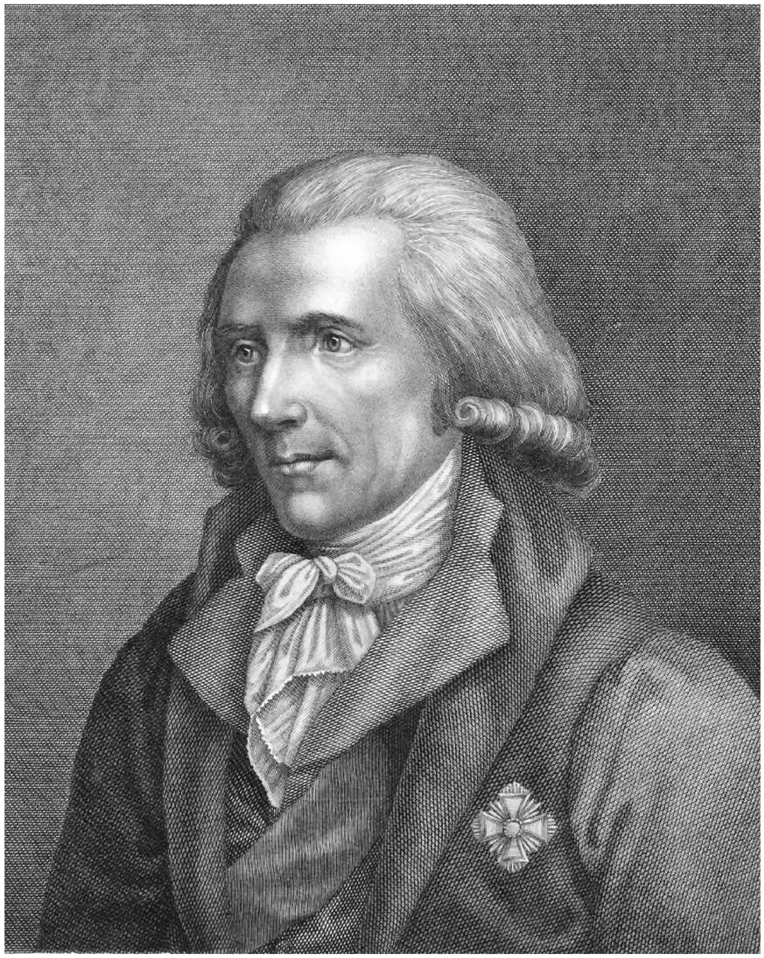

Figure 1: Benjamin Thompson, Count Rumford (1753-1814) (Smithsonian Institution Libraries Digital Collection)

much older wealthy land owner who died after one year of marriage. Less than a year after Sarah was widowed, Thompson married her in 1772 when he was 19. Thompson's new wealthy wife facilitated his connections with the British governing class, in particular by dressing him up in a fine Hussar uniform and parading him about Boston, where he made such an impression on Governor John Wentworth that he was given a British major's commission in the 2nd New Hampshire Regiment. In 1774 Thompson and his wife had a daughter – also Sarah.

By this time hostilities between the Colonies and the Crown had been mounting; these included the Stamp Act and subsequent riots (1765), the Boston Massacre (1770), and the Boston Tea Party (1773), which was followed by both the relocation of the Massachusetts capitol from Boston to Salem and the passing of a series of Acts called, by the colonists, the Coercive Or Intolerable Acts. These events had by now led to the First Continental Congress in Philadelphia in September 1774 which demanded repeal of these acts, as well as calling on civil disobedience and the buildup of local militia called the Minutemen. Eventually war broke out near Boston in April 1775, at Lexington and Concord.

Benjamin Thompson's acceptance of a British commission in the 2nd New Hampshire Regiment was thus problematic for several reasons. While British officers resented the presence amongst their ranks of an inexperienced schoolmaster, the people of Concord and Woburn regarded him as a traitor and he had to face two trials for “being unfriendly to Liberty”, in 1774 and 1775, both of which weathered without formal charges. Nevertheless, Thompson left for Boston in 1775 to offer his services to the British Army, in particular to gather intelligence on rebels by various and nefarious means. In March 1776 the British evacuated Boston and Thompson left with them, abandoning his wife and daughter; he was never to see his wife again, and his daughter not again for 20 years.

In England, Thompson worked for the Secretary of State for the Colonies, and he rose rapidly to other prominent positions in the administration of colonial rule. During this time, around 1778, his studies of force and heat associated with gunpowder explosions and ballistics of large guns led to his election as Fellow of the Royal Society in 1781.

Thompson also briefly went back to the American colonies in 1781 to take up command in the King’s American Dragoons in New York. With the end of the war shortly thereafter, Thompson returned to England as a professional soldier and colonel, and went to the continent as a soldier of fortune in 1783, landing in Bavaria, eventually to become the advisor to Elector Karl Theodor. As a consequence of his new employment, he was knighted by the British King George III in 1784 to secure his loyalty to England. It was in Bavaria, with the financial and technical backing of his court position, that Thompson did much of his scientific work, especially on insulating properties of materials and on transport of heat by fluids (i.e., convection). He also did much in terms of military, educational, social and economic reform in Bavaria, all for which he was rewarded by being made a Count of the Holy Roman Empire in 1792; he assumed the title of Count Rumford adopting the original name of the New Hampshire village where his rapid climb began.

Rumford’s frenetic activity and modern innovations met with great resistance by the established order who eventually held sway with the Elector and caused Rumford to be removed back to London as a Minister to the English Court. However, due to a miscommunication with the British Crown, he arrived jobless in London. Unable to remain idle, Rumford established the Royal Institution in London which employed natural philosophers like Thomas Young and Humphrey Davy to perform experiments and give public lectures. However, his dominating style and large ego led to battles with Institute managers and he eventually left both the Royal Institute and England in 1802. He flitted for political reasons between Bavaria and France, until the invasion of Bavaria by Austria in 1805 sent him permanently to France, where he hoped to gain favor with Napeoleon Bonaparte. In France he married the widow of the “father of chemistry” Antoine Lavoisier who had been sent to the guillotine at the height of the French Revolution in 1794. However, in France, Rumford fought scientifically with Laplace and Lagrange and separated from Madame Lavoisier de Rumford. He died in August 1814, and was buried in the village of Auteuil.

Rumford was of course known widely for his philosophic papers on the nature of heat and mounted perhaps the most coherent assault on the caloric theory. The caloric theory is – as with many failed theories – frequently explained with hindsight as an absurdity. However, it is important to understand that it was a reasonably sophisticated physical and mathematical theory that made distinct quantitative predictions about the nature of both heat and matter that were in fact born out by experiments. Caloric was considered the medium or “fluid” that transported and retained heat within matter. But more specifically, caloric was thought to provide the repulsive force – by providing a caloric atmosphere around each atom – within matter to keep it from collapsing under the influence of gravitational attraction. The mathematical predictions of the caloric theory were born out by the experiments of Dulong and Petit on, for example, thermal expansion. Similarly, predictions about dependence of specific heat on temperature, phase changes (in which caloric is either absorbed or released), adiabatic heating under pressurization (wherein caloric is squeezed out), and heat conduction as driven by caloric potential all verified the caloric theory. Indeed, the notion of caloric substance remains a relic in our discussion of heat as "flowing", or existing as quantities with certain densities such as specific heat or latent heat [Brown, 1967].

Thus, Rumford's assault on caloric theory was not on a ludicrous model that could be easily dispatched by simple thought experiments. However, it did conflict with certain observations, a few key ones Thompson was responsible for. Most notably these included his work on frictional heating, in particular his observation that during work on boring out cannons, heat is created with no evident source of caloric from other matter; and also the propagation of heat in a vacuum by radiation (as caloric was thought to exist only in proximity to atoms).

Rumford's observations of thermal convection. Rumford's work on thermal convection was a rather famous paper that was published in multiple venues in 1797 [Thompson, 1797; Brown, 1967] during his tenure in Bavaria. Much of this work involved the investigation of the insulating properties of matter, which he was investigating as part of an effort to improve cold-weather clothing for field soldiers, as well as the poor and under-classed. But this work was also relevant in his attack on caloric theory in that it showed that heat could be transported by the motion of mass itself, and if such mass flux did not occur the material was an insulator (or nearly so). This also prompted him to note that the internal motion of fluid particles also provided a ready source of heat and this was a precursor to his theory of heat as particle motion.

Rumford's most explicit observation of convection itself occurred while examining the "communication of Heat" by taking over-sized thermometers filled with liquids (including alcohol derived from wine) and subjecting them to heating. Upon leaving one thermometer in a window to cool, Rumford noticed rapid fluid motion that was well delineated by dust particles (which had been introduced because he had let the tubes sit open for two years without cleaning) illuminated by the sun light:

> I observed an appearance which surprised me, and at the same time interested me very much indeed. I saw the whole mass of the liquid in the tube in a most rapid motion, running swiftly in two opposite directions, up and down at the same time [Thompson, 1797].

On closer inspection Rumford noticed a regular circulation of upwelling along the axis of the tube and downwelling along the cooler glass boundary. He further found that dousing the tube with ice water hastened the motion, but that the circulation eventually ceased as the entire thermometer reached room temperature.

Rumford reasoned that heat in liquids and gases was only carried by particle motion and to prove this he contrived experiments in which the fluid was subjected to thermal gradients but the particle motion was obstructed or "embarrassed". He compared heat transport in water, when pure and when mixed with substances such as eider (duck) down and stewed apples, which would "impair its fluidity". Rumford concluded that, "Heat is propagated in water in *consequence* of internal motions or that it is transported or carried by the particles of that liquid...." The manner in which heat transport can be inhibited by impaired fluidity led Rumford to speculate on the role of convective heat transport in nature, in particular that impaired fluidity was God's design, for example observing that

> ... when we advert to the additional in-

> creased viscosity of the [tree] sap in winter, and to the almost impenetrable covering for confining Heat which is formed by the bark, we shall no longer be at a loss to account for the preservation of trees during winter.. [Thompson, 1797]

Rumford had in fact noted an important feature of convection in many natural systems; i.e., the concept of self-regulation of heat during convective heat transport. This is something considered also in mantle convection, in particular that high temperatures lead to low viscosity and rapid convective expulsion of heat, while low temperatures lead to greater effective insulation and eventual build up of heat.

Count Rumford was in every sense an experimentalist and observationalist, but his contributions to the study of heat marked the initiation of the modern theory of classical thermodynamics, kinetic theory, and heat transport by particle motion both microscopically and through thermal convection.

Further reading, including sources for this brief history are S. Brown [1967] and G. Brown [1999].

7.01.2.2 John William Strutt, Lord Rayleigh (1842-1919)

The contributions that John William Strutt made to various fields of physics is evident in the number of phenomena named for him, including Rayleigh scattering, Rayleigh-Jeans criterion, Rayleigh waves, and within the study of convection the Rayleigh number. His greatest legacy is perhaps his contribution to the theory of waves in solids and fluids; however, he received the Nobel prize in Physics for the discovery and isolation of atmospheric argon, which was essentially experimental chemistry.

Although Strutt was one of the few noble scientists actually born into nobility (as opposed to say Benjamin Thompson who was ennobled in his own life) the Strutts were not from ancient noble stock. The family could be traced back to 1660, where it was known for milling corn with water-driven mills, a business that eventually established the family's financial standing. In 1761 John Strutt (Rayleigh's great grandfather) purchased what eventually became the family estate of Terling Manor, and where Rayleigh would eventually build his laboratory in which he did much of his science. John Strutt's oldest surviving son Joseph Holden was a Colonel in the West Essex Militia, and a Member of Parliament (like his father); for his public services he was offered a peerage by George III. However, for not entirely clear reasons, other than an apparent conviction not to accept personal honors, Joseph Strutt declined the peerage and asked that it be bestowed on his wife Lady Charlotte (Fitzgerald) Strutt, whom he had married in 1789. When she died in 1836, the peerage went to Joseph's only son John James, who became the Second Baron Rayleigh, during his father's own lifetime. The name Rayleigh was in fact after a small market town in Essex (and possibly for no particularly deep reason other than its noble sound). John James married Clara Vicars in 1842 (nearly 30 years his junior); in biographies of Rayleigh, it was usually claimed that his scientific and mathematical talent came not from the Strutt's but from the Vicars, who boasted several members of the Royal Engineers and direct descendency from the brother of physicist Robert Boyle. In November of the year of their marriage, John William Strutt, oldest son and heir to the barony, was born, prematurely. As a child he did not speak properly till past the age of 3, prompting his grandfather Colonel Strutt to remark that "That child will either be very clever or an idiot" [Strutt, 1968]).

John William suffered poor health throughout his youth and had to be withdrawn from school twice to be tutored privately. He entered Trinity College Cambridge in 1861 where he studied rigorous mathematics with, for example, Sir George Stokes, the Lucasian Professor of Mathematics, and graduated with honors in 1865. Immediately after graduating Strutt opted not to go on the traditional grand tour of

Figure 2: John William Strutt, Third Baron Rayleigh (1842-1919) (AIP Emilio Segre Visual Archives, Physics Today Collection)

the "continent", but rather visited the United States, which was then in throws of post-Civil War Reconstruction. Upon his return to America he purchased experimental equipment to set up his own laboratory. There was at the time no formal university physics laboratory in Cambridge; although much experimental work had already been done by the likes of Michael Faraday, Humphrey Davy and even Isaac Newton, most of this was outside the university (in particular at the Royal Institution, which, as noted above, was founded by Count Rumford). It was not until 1871 that James Clerk Maxwell was named the First Cavendish Professor of experimental physics, and not till 1873 that the Cavendish labs were built.

Strutt's first paper in 1869 was on Maxwell's theory of electromagnetism, for which he received much

[1]Arthur James Balfour became British Prime Minister from 1902-1905 and was the author of the Balfour Declaration (1917) in which Britain formally supported the creation of a Jewish homeland in Palestine during the partitioning of the Ottoman Empire after World War I.

encouragement from Maxwell himself. In 1871 he married Evelyn Balfour, the sister of Arthur James Balfour[1]. However, soon after his marriage, Strutt had a seious bout of rheumatic fever, which prompted a lengthy tour of Egypt; during these travels he did much of his work on his famous book *The Theory of Sound*. After his return in 1873, he assumed the title of Third Baron Rayleigh on the death of his father, and and took up residence in Terling where he built his lab in which he did much of his life's scientific work. His book on sound was published in 1877 and 1878 (in 2 volumes), an achievement which emphasized his life-long fascination with sound and wave theory in general. During these early years he also continued to work on sound, electromagnetism, light, as well as his theory for light scattering and the cause of the sky's blue color.

James Clerk Maxwell's untimely death in 1879, at the age of 48, left the Cavendish Experimental Chair vacant. The first Cavendish Chair had been offered to Sir William Thomson (later Lord Kelvin) in 1871, but he had refused in order to stay in Glasgow, and his decision remained even upon being re-offered the job in 1879. Rayleigh was then offered the position and reluctantly decided to take it because he needed the money given that revenue from Terling had dropped off during the agricultural depression of the late 1870s. Indeed, Rayleigh only held the position until 1884 after which his economic situation had improved and he returned to his residence and work in Terling. His brief tenure as the Cavendish Professor was the only academic position he held in his life. However, during his time in Cambridge he carried out a vigorous program of experimental instruction and research on electrical standards, now having access to lab assistants and more facilities. Also in his years at Cambridge he developed a close acquaintance with Sir William Thomson.

After resigning his professorship and returning to Terling, Rayleigh became Secretary of the Royal Society for the next 11 years (1885-1896). In 1887, he became Professor of Natural Philosophy at the Royal Institution (see Section 7.01.2.1) at which he gave over a hundred lectures until he left it in 1905.

One of the discoveries that Rayleigh is most noted for is his discovery of argon in the atmosphere. Rayleigh had first suggested the presence of an unknown atmospheric gas because of an apparent anomaly in the density of atmospheric nitrogen relative to that extracted from compounds. Later he did careful and difficult experiments separating argon from atmospheric gas in 1895. William Ramsay, following up on Rayleigh's earlier suggestion, also conducted experiments to extract argon. Some controversy ensued over whether Ramsay had a right to follow Rayleigh's suggestion and infringe on his research. But even Rayleigh himself agreed that publication of an idea makes it, in effect, public domain, which is very much the prototype of modern publication ethics today. The two shared priority of the discovery for which they each received the Nobel Prize in 1904, Rayleigh's in Physics and Ramsay's in Chemistry.

Rayleigh became President of the Royal Society from 1905-1908, and took on numerous public service roles, chief of which was Chancellor of Cambridge University in 1908. He published his complete papers up to 1910 in 5 volumes; the remaining papers from 1911-1919 were published posthumously under the editorship of his son Robert John (who was himself a prominent physicist; see Section 7.01.2.4) in 1920. Rayleigh was author of approximately 450 papers, working essentially up to his death in June 1919; indeed, 3 of his papers were still in review or in press on the day of his death.

Rayleigh's linear theory of convection. Lord Rayleigh's paper on convection was written very late in his life, in 1916, only three years before his death [Strutt, 1916]. He had, however, worked sporadically on the stability of fluid flows since at least the 1880s. Rayleigh's paper on convection was entirely inspired by Bénard's experiments which had taken place 15 years earlier (Section 7.01.2.3). In his 1916, paper

Rayleigh described Bénard's experiments, recognizing two phases, which were an initial transient phase in which an irregular or semi-regular pattern is established (with polygons of 4-7 sides) and then a second phase of stable and regular polygonal patterns. In a footnote he also commented that Bénard was perhaps unaware of the work of James Thomson (Lord Kelvin's older brother) who did fundamental work on evaporative convection finding similar polygonal patterns [see Berg et al., 1966]. Rayleigh's theory was in fact focussed on the first phase, or the transient onset; he did not recognize in the second phase what was later termed "exchange of stabilities" in that the state to which the perturbations are moving the system is itself stable and non-oscillatory [see Chandrasekhar, 1961]. Rayleigh followed a first-order perturbation analysis, although in a rather informal manner. He explored the effect on stability of various individual parameters (e.g., viscosity – considering both inviscid and viscous cases, thermal diffusivity, sign of imposed temperature gradient, gravity, and thermal expansivity), but did not recognize dynamic similarity and dependence on a few dimensionless numbers (see Ch.4 this volume). Although he did not pose the dimensionless number called the Rayleigh number, it is easily recognizable in his solution for the minimum critical temperature gradient or "density drop" across the layer (Strutt [1916] equations (44) and (46)). Rayleigh also commented on the degeneracy of the linear problem (i.e., mode selection only in terms of wave-number squared). But he also recognized that the basic differential operators in the equations allowed wavenumber pairs that permitted regular polyhedral patterns such as squares and rolls, although he admitted that while hexagons and triangles were obvious, the problem was not immediately tractable (it was, however, later solved analytically; see Chandrasekhar [1961]). Bénard's hexagonal patterns were cause for some confusion in the comparison of theory and experiment, and they were later inferred to be characteristic of systems where vertical symmetry of the convecting fluid layer is broken (e.g., with temperature-dependent viscosity; see Manneville [2006] and Section 7.01.2.3).

Lord Rayleigh's paper is of course one of the great seminal works in the study of convection, not just for establishing the the theoretical framework of the problem and developing the concept of marginal stability, but also for inferring pattern selection at convective onset. Further reading and sources for this history can be found in Strutt [1968] and Lindsay [1970].

7.01.2.3 Henri Claude Bénard (1874-1939)

While the phenomenon of thermal convection had been observed at least as early as the accounts of Count Rumford (Section 7.01.2.1), Henri Bénard is widely recognized for having done the first systematic quantitative examination of natural cellular convection. Even given all the problems later found with his experimental results, he is justifiably recognized as the father of experimental studies of convection, which later inspired decades of work not only on convection but also on self-organization and critical phenomena [Wesfried, 2006; Manneville, 2006].

Henri Claude Bénard was born in Lieurey, a small village in Normandy, in October of 1874. His father was a financial investor who died when Bénard was young. After attending schools in Caen and later Paris, Bénard was, in 1894, accepted into the highly competitive Ecole Normale Supérieure de Paris, one of the French Grand Ecole's, in a year with about 5% acceptance rate in the sciences. While at the ENS-Paris he studied with some very notable classmates, for example, physicist Paul Langevin and mathematician Henri Lebesgue, and was witness to the groundswell of outrage over the Dreyfus Affair. In 1897 he received the *agrégé de physique* (now termed *agregation*, whereby state teaching credentials are obtained) and began work in the department of experimental physics in the Collége de France, which is unattached to any university and does not

Figure 3: Henri Claude Bénard (1874-1939) (From Wesfried [2006], Fig. 2.3, p.15. With kind permission of Springer Science and Business Media.)

grant degrees, but provides open public lectures (similar to the Royal Institution). While there, Bénard was assistant to Eleuthère Mascart and Marcel Brillouin, who were, respectively, grandfather and father of the physicist Leon Brillouin [Wesfried, 2006]. While at the Collége de France, he worked on the rotation of polarized light through sugar solutions, which gave him training in the use of optics for measurements of fluid motion; this specific work also led to the second topic of his Ph.D. thesis, which was then required for the French doctorate.

The experiments on convection for which Bénard is well known today [Bénard, 1900, 1901] were the primary part of his Ph.D. thesis, but the topic was arrived at much by accident (see below). In the defense of his thesis on March 15 1901, his committee found the work satisfactory but less than inspiring, criticizing Bénard because, while it was innovative (mostly interesting in its application of optical methods) and above average, it was disappointing in that it provided no general theoretical development to explain the experiments. The report on his defense stated that "though Bénard's main thesis was very peculiar, it did not bring significant elements to our knowledge. The jury considered that the thesis should not be considered as the best of what Bénard could produce" [Wesfried, 2006]

After his thesis in 1900 he briefly settled in Paris, got married (but had no children) and was shortly thereafter appointed to the Faculty of Sciences in Lyon (1902). In Lyon, Bénard carried out much of his well-known work on vortex shedding around bluff (prismatic) bodies, and further developed his ingenious employment of cinematography in laboratory experiments. In 1910 he was appointed to the Faculty of Science at the University of Bordeaux in physics under the department head Pierre Duhem.

With the outbreak of war in 1914, and as a former student of the Ecole Normale, which carried with it state obligations, Bénard entered the military and was made an officer. He was put on a military scientific commission wherein he worked on problems relating to food refrigeration under transport, and, later, on the military use of optics (e.g., using polarized light for tracking ships and submarines, and for improving periscopes)

After the war Bénard returned to science, and in 1922 he moved to Paris as professor in the Sorbonne

University. In 1928 he became the President of the French Physical Socieity. In 1929 he participated in the development of the Institute of Fluid Mechanics, and in 1930 became professor of experimental physics. For the next decade he continued to work with various students on convection and vortex shedding. He died in March 29, 1939, slightly shy of 65.

Bénard's experiments on convection. Henri Bénard's first observations of cellular convective motion came in 1898, at the Collége de France, while trying to make a coherer of solid dielectrics (a coherer is a loose often granular agglomeration of conductors or semiconductors whose conductivity is affected by impingement of radio waves). In the preparation he noticed a polygonal pattern in melted paraffin that had graphite dust in it. From there Bénard detoured into a painstaking and systematic study of convection, in particular the difficult task of finding the onset of convection as near to conductive stability as possible. To carry out this task meant eliminating minute thermal fluctuations imposed at the boundaries, and so Bénard constructed an apparatus comprised of a metal container with steam circulation in its walls to provide a nearly uniform isothermal bottom boundary; the top however was exposed to air. Bénard observed different patterns of convection cells which had polygonal structure of 4-7 sides (see also Section 7.01.2.2 as well as Ch.3 this volume), but were predominantly hexagaonal. He termed these cells *tourbillons cellulaires* or cellular vortices, although we now refer to them as Bénard cells or convective cells. Bénard was able to measure closed streamlines of particle flow, and observed an initial transient state of polygon formation, settling down to a stable hexagonal configuration after some time, which allowed him to measure cell sizes accurately. He also observed convective rolls (or *tourbillons en bandes*, what Rayleigh later referred to as striped vortices), which occurred at low heat flux, as well as high-heatflux turbulent "vortex worms". What is highly notable is the large number of innovative optical techniques Bénard used and developed. He not only introduced the use of cinematography, but also particle trajectories, interference fringes due to light reflected off hills and valleys on the convectively warped free surface, and also transmission across the fluid layer, which is essentially the same as the shadowgraph technique commonly used today (see Ch.3 this volume). The combination of these optical effects in fact allowed him to estimate isotherms with (quite impressively) 0.1^oC contours.

Years later, in 1916, Rayleigh analyzed Bénard's experiments (see Section 7.01.2.2), but assumed free-slip top and bottom boundaries (which was an analytically tractable configuration of boundary conditions). Rayleigh's work confirmed some of the patterns observed by Bénard, but not the critical conditions for convective onset (what we now call the critical Rayleigh number) due to the inappropriate boundary conditions. Because of World War I, Bénard was not aware of Rayleigh's work until the 1920s, well after Rayleigh's death. In the late 1920's and early 1930's, Bénard compared his experiments to the theoretical work of Sir Harold Jeffreys who had repeated Rayleigh's stability analysis but with the appropriate mixed boundary conditions of a free-slip top and a no-slip bottom [see Wesfried, 2006]. Bénard found the patterns predicted in Jeffrey's work matched some of his experiments, but the conditions for convective onset still did not agree, implying a significant disparity between theory and Bénard's experiments.

Bénard was aware at the time of his first experiments of problems inherent with an open surface, but he was mainly concerned with the fact that some working fluids, especially volatile ones such as alcohol, experienced evaporative convection, which is often coincident with Marangoni (surface tension driven) convection [see Berg et al., 1966]. Bénard thus used fats or oils (i.e., spermacetti) and wax that had higher melting temperature and thus lower vapor pressures. Block [1956], however, repeating Bénard's experiments, later suggested that thermally induced surface tension gradients, rather than thermal buoyancy, were the cause for the observed motions and surface deflection; surface-tension driven convection, now known as Marangoni-Bénard convection, was formally developed by Pearson [1958].

Throughout his life, Bénard continued to make analogies between the cells of his experiments and natural ones, in some cases incorrectly (e.g., Taylor-Couette rolls). However, he correctly advocated the cellular cause of solar granulation. Moreover, he promoted the idea that cloud streets were due to longitudinal convective rolls aligned parallel to wind; he directed experiments on convection in a tilted layer, and ones with a moving top boundary, to find alignment of convection rolls [see Wesfried, 2006, and references therein], essentially identical to what it is refered to in mantle dynamics as Richter rolls (see Ch.7 this volume).

Additional reading and historical sources for this brief history are Wesfried [2006] and Manneville [2006].

7.01.2.4 Arthur Holmes (1890-1965)

The prospect of convective heat transport in the mantle was alluded to possibly as early as the early to mid 19th century [e.g., Schubert et al., 2001; England et al., 2007]. However, Arthur Holmes can rightly be considered one of the founders of the physical theory of mantle convection as it pertains to the driving mechanism of continental drift. Even so, Holmes is still perhaps most well known for championing the science of radiometric dating to infer the age of the Earth, and for establishing the geologic time scale [Lewis, 2000].

Arthur Holmes was born in Gateshead, in the northeast of England, in 1890. As a precocious teenage student, he was strongly influenced by a teacher who introduced him to both physics and geology through the writings of William Thomson (Lord Kelvin) and the Swiss geologist Edward Suess. At the age of 17 he went to London to study physics at the Royal College of Science, which was then being absorbed into the new Imperial College London, but then changed directions to geology. However, his background and interest in physics would serve his geological ventures throughout his life. In his final year at Imperial College he studied the novel and exciting phenomenon of radioactivity, and the prospect of radioactive dating of rocks, under the new young professor Robert John Strutt, the son of Lord Rayleigh. Strutt had himself been involved in a vigorous and public debate over the age of the Earth with his father's old friend, Lord Kelvin [Lewis, 2000].

The debate over the age of the Earth is traditional historical fare in geoscience [see Lewis, 2000]. Suffice it to say that the controversy swirled about both Bishop Ussher's biblically inferred age of 6000 yr and Lord Kelvin's cooling age of 20 Myr, neither of which could be reconciled with geologists observations of sedimentation rates that required the oldest rocks to be no less than 100 Myr old. However, the discovery of radioactivity in rocks and the resolution of radioactive half-lives, suggested a nearly direct measure of rock ages. (It also provided a heat source for keeping the Earth from having to cool from a recent molten state.) Several scientists attempted to develop the technique of radiometric dating, including R.J. Strutt and Ernest Rutherford. But, in the end, Yale scientist Bertram Boltwood identified lead as the final product of the uranium-radium decay series; since lead was a non-volatile and thus a non-leaking daughter product – unlike helium – it's concentration could be reliably measured. Boltwood used this decay series to infer the age of rocks in both Connecticut and Ceylon (now Sri Lanka) and determined ages of these rocks between 535 Myr to 2.2 Gyr and published these results in 1907 [see Turekian and Narendra, 2002]. Using Boltwood's method, Holmes similarly dated Devonian rocks and arrived at an age of 370 Myr; his results were presented (in his absence) at the Royal Society in 1911.

Indeed, by 1911, Holmes was already in Mozambique where he had taken a job in mineral prospect-

Figure 4: Arthur Holmes (1890-1965). Used with permission from the Arthur Holmes Isotope Geology Laboratory at Durham University.

ing because his scholarly stipend in London was not enough to live on. However, he was there only 6 months, having fallen seriously ill with malaria. He returned to London to take a job as demonstrator in the Imperial College where he continued to push the geochronological methods. In 1913 Holmes published his first book, at the age of 23, *The Age of the Earth* where he calculated the planet's age to be 1.6 Gyr old, which was less than Boltwood's estimate. Although geologists were, on the whole, relieved that the 6000 yr and 20 Myr ages were proven wrong, many still held fast to the 100 Myr date and were reluctant to accept the radiometrically inferred ages, probably because many did not understand the new physical principles of radioactivity [Lewis, 2000, 2002]

Holmes married Margaret (Maggie) Howe in 1914 and he continued working as a demonstrator in the Imperial College through World War I. After the birth of his son Norman, in 1918, Holmes found that he was unable to support his small family on his demonstrator's salary, and thus took a job prospecting for oil with a company in Burma in 1920. However, the company soon went bankrupt. Moreover, Holmes' four-year-old son Norman fell ill with dysentery and, despite available medical attention, died in 1922. Holmes and his wife soon returned to England, impecunious and grieving. His misfortunes continued, however, and he could not find a position until 1924 (in the meantime running a curio shop for income), when he was offered a professorship at the University of Durham to build a new geology department.

Holmes remained at Durham for nearly 20 years. In that time he produced his now famous papers on mantle convection as the cause for continental drift (see below) and wrote his text *Principles of Physical Geology*, the first edition of which appeared in 1944. However, also during those years Holmes' wife Maggie died (in 1938), but he was soon thereafter remarried to Doris Reynolds, a fellow geologist.

Holmes left Durham in 1943 to assume the Regius Professorship at the University of Edinburgh where he remained until retirement in 1956. While at Edinburgh he continued to work on refining the age of the Earth and developing the geologic time scale, in addition to other geological pursuits. He received various high honors (e.g., the Wollaston and Penrose medals in 1956; and Vetlesen prize in 1964), primarily for his work on the geologic time scale, not on continental drift and convection. In the early 1960s evidence for plate tectonics was mounting, especially with the Vine-Matthews work in 1963 on seafloor spreading. Holmes' sense of vindication is evident in his revised text, which was published the year he died, in 1965.

Holmes and mantle convection. By the late 1920s and early 1930s the debate over the age of the Earth had given way to a new controversy over the theory of Continental Drift. As is well known, the German Meteorologist Alfred Wegner had proposed his idea based largely on geographical evidence [Wegener, 1924; Hallam, 1987]. But he also proposed that continents plowed through oceanic crust like ships, and the driving force was due to centrifugal effects. Although Sir Harold Jeffrey's had done some of the most fundamental work on convection theory (see Schubert et al. [2001] and Section 7.01.2.3), he had argued that there were no available forces sufficient to deform the Earth's crust during continental drift. Holmes, on the other hand, supported the idea of Continental Drift but, along with Bull [1931], proposed that subsolidus convection in the mantle – powered by heat production from radioactive decay – was instead the driving mechanism for continental breakup, seafloor formation (not spreading), crustal accumulation at convergence zones and continental drift [Holmes, 1931, 1933]. Holmes' ideas of subsolidus convection were similar to present day understanding. Some notable differences his model has with contemporary mantle convection theory are that Holmes believed that mantle flow would establish jets and prevailing winds as in the atmosphere, although these in fact arise through the combination of convection and planetary rotation; as discussed in Chapter 2, this volume, the effects of rotation are not significant in mantle circulation. Moreover, Holmes also proposed that seafloor formation was associated with deep and active mantle upwellings, which was later proved to be unlikely even as early as the 1960s (see Section 7.01.2.7). Holmes' theories of convection were, like Wegener's theory of continental drift, rebuffed and ignored, although Holmes continued to teach these ideas while at Durham and Edinburgh; indeed his famous text contains a final chapter discussing his view of continental drift and convection.

Further reading and sources for this section can be found in Hallam [1987], Lewis [2000, 2002] and Schubert et al. [2001].

7.01.2.5 Anton Hales and Chaim Pekeris

Arthur Holmes is largely seen as a visionary in being the champion of convection as the driving mechanism for continental drift. However, near the same time as his first papers, two important papers on mantle convection were published, i.e., by Anton Hales [Hales, 1936] and Chaim Pekeris [Pekeris, 1935]. Both of these used modern fluid dynamic theory to estimate not only the conditions for convection, as Holmes had done, but also to calculate the finite-amplitude velocity and stresses of convective currents, and to compare them with predictions from gravity observations. Not only were their theories fluid dynamically sophisticated, but their predictions were born out 30 years later in measurements of plate motions. Moreover, their respective papers were precursors to the modern analysis of how convection is reflected in gravity, geoid and topography. Thus these two authors warrant some discussion. Both Hales and Pekeris were perhaps better known for their life-long contributions outside of mantle dynamics (e.g., seismology) but they both played important roles in the growth of geophysics in the 20th century.

7.01.2.5.1 Anton Linder Hales (1911-2006)

Anton Hales was born in Mossel Bay, in the Cape Province of South Africa in March 1911. As with all our historical subjects, Hales showed an early aptitude and talent for science and graduated from the University of Capetown with a B.Sc. in physics and mathematics, at the age of 18, and a M.Sc. at 19. He then, in 1931 at the age of 20, took up a post as a Junior Lecturer in mathematics at the University of Witwatersand in Johannesberg [Lilley, 2006]. However, after only one more year he received a scholarship to study at Cambridge. Although intending to study quantum mechanics, he was convinced by Sir Basil Schonland (a senior lecturer in physics at the University of Capetown) that this was the “wrong choice” [Lambeck, 2002] and that he should instead study geophysics. Thus, while in Cambridge, Hales studied with Sir Harold Jeffreys and interacted with Keith Bullen, and received his B.A. in mathematics from St. John’s College in Cambridge in 1933.

Hales returned to South Africa where he resumed his post as Junior Lecturer and eventually Senior Lecturer in Applied Mathematics at the University of Witwatersand. While there he also carried out research primarily in seismology for which he received his Ph.D. from the University of Capetown in 1936. That year Hales married Marjorie Carter with whom he had two sons James and Peter [Lilley, 2006].

At the outbreak of the Second World War, Hales scientific career was put on hold and he served as an Engineering Officer in the North African campaign. After the war, Hales left his lecturer position to become a senior researcher at the Bernard Price Institute for Geophysical Research at University of Witwatersand where he worked on development of seismic and gravity measurement methods. However, in 1949, he left BPI for a Professorship in Applied mathematics and the Head of the Mathematics Department at the University of Capetown. During these years he went briefly to Cambridge (1952) to receive a Masters Degree. In 1954 he returned to Witwatersand as Director of BPI and Professor of Geophysics. While Director of BPI he continued to push development of geophysical methods, including paleomagnetism, and he was involved with some of the first measurements anticipating plate tectonic motions by looking at pole paths in South Africa, which began to convince Hales of the validity, after all, of continental drift [Lambeck, 2002]. It was also during his time at BPI, in 1957, that Marjorie, his wife of 21 years, died.

In 1962 Hales left South Africa for the United States to become the founding director of the Geoscience Division for the Southwest Center for Advanced Studies, later to become the University of Texas. That year he also remarried to Denise Adcock with whom he had two more sons, Mark and Colin. While in Texas, Hales continued to build a powerful research institute and made major contributions to seismic studies of the crust and upper mantle.

In 1973, at the age of 62, Hales was convinced (most notably by Ted Ringwood and John Jaeger [Lambeck, 2002]) to move to the Australian National

Figure 5: Anton L. Hales (1911-2006). Used with permission from the Department of Geosciences of the University of Texas at Dallas.

University to become the founding director of the Research School of Earth Sciences (RSES) where he served until 1978. Hales was an active and unique director in that he minimized departmental structure and bureaucracy and pushed his scientific staff to work globally rather than on regional Australian studies, thereby establishing the School's reputation as one of the worlds foremost Earth science institutes. Moreover, under his Directorship the SHRIMP ion microprobe – then a very new and expensive technological advance in geochemical analysis– was developed.

Hales retired from ANU in 1978 and returned to the University of Texas as Professor of Geophysics. He retired from the University of Texas shortly thereafter in 1982, and returned to ANU and RSES to resume his position as Emeritus Professor until 2002. By the time of his retirement he had been made a Fellow of the Royal Society of South Africa, the American Geophysical Union, and the Australian Academy of Sciences; in 2003 he was given the Centenary Medal from the Australian government. Hales stayed in and around Canberra for the remainder of his life. However, in 2004 his son Mark from his second marriage was tragically killed in a car accident [Lilley, 2006], only two years before Anton Hales himself passed away, in December of 2006, at the age of ninety five.

Hale's and convection in the mantle. Anton Hale's work on the viability of mantle convection occurred during his doctoral studies but was unrelated to his dissertation research; his paper on the subject was published in 1935 before receiving his Ph.D. The problem he examined, suggested to him by Harold Jeffreys, concerned the plausibility of convection with regard to whether the buoyant stresses driven by a mantle of a certain viscosity and heat input were consistent with those inferred by the gravity anomalies measured during the famous submarine gravity surveys of F.A. Vening Meinesz. To calculate convective stresses, Hales estimated convective velocities by equating mid-mantle advective heat transport with the conductive surface heat transport necessary to remove the net radiogenic heat production. Hales' relationship for his velocities could be shown to yield very plausible tectonic velocities, as mentioned by Jeffrey's himself in the later editions of his famous text [Jeffreys, 1959]. (Similarly, as shown in Bercovici [2003], a simple balance of the net advective heat extraction by slabs of a given mean temperature anomaly against the known mantle cooling rate predicts quite readily slab velocities of 10 cm/yr.) Hales used these velocities to estimate the stresses of convective currents, and compared these with the stresses necessary to support mass anomalies inferred from gravity measurements. Although Jeffrey's no doubt believed that convective stresses in a stiff mantle would be far in excess of those predicted by gravity, Hales showed that the stress estimates were in fact very close and easily permitted a convecting mantle. Jeffrey's "communicated" (i.e., sponsored) his former student's findings to the Royal Astronomical Society for publication [Hales, 1936].

Further reading, including sources for this brief history are Lambeck [2002] and Lilley [2006].

7.01.2.5.2 Chaim Leib Pekeris (1908-1993)

Chaim Leib Pekeris was born in Lithuania, in June 1908 in the town of Alytus, where his father was a baker. He was the oldest of 5 siblings, and had two brothers and two sisters. As a youth he was (unsurprisingly) precocious in mathematics, and was apparently teaching highschool math by age 16. In the 1920s he and his two brothers emigrated to the United States with the help of family and friends already in America [Gillis, 1995; Gilbert, 2004]. The three Pekeris brothers became American citizens and continued their education in the U.S. In contrast, one of his sisters moved to Palestine in 1935 as a Zionist. The remaining sister and their parents were, however, later murdered by anti-Semites in Alytus during the Holocaust.

Chaim Pekeris entered the Massachusetts Institute of Technology (MIT) in 1925 to study meteorology, and obtained his B.Sc. in 1929. He stayed on for graduate work with Carl-Gustave Rossby and obtained his doctorate in 1933. During his graduate career he was also a Guggenheim Fellow and studied meteorology in Oslo. After finishing graduate studies, he became an assistant geophysicist in the Department of Geology at MIT, and from there rapidly transitioned away from meteorology. He also received a Rockefeller Foundation Fellowship in 1934, and at the same time was married to Leah Kaplan.

Pekeris had been hired at MIT by Louis Slichter who had himself been hired by MIT to establish a geophysics program. Pekeris was his first hire and the second was Norman Haskell, a new Ph.D. from Harvard. The combination of Pekeris and Haskell during the early 1930s made important contributions to the burgeoning problem of continental drift and mantle flow. As is well known, Haskell was to perform the first analysis of Fennoscandian uplift from which the viscosity of the mantle was initially estimated [Haskell, 1937]. In conjunction, Pekeris did a "hydrodynamic" analysis of thermal convection in the Earth's mantle, which led to an accurate first or-

Figure 6: Chaim L. Pekeris (1908-1993). From Gilbert [2004]. Reprinted with permission from the National Academies Press Copyright 2004, National Academy of Sciences.

der estimate of mantle flow and velocities (see below).

Chaim Pekeris also worked on free oscillations, but in particular of stellar atmospheres, although this laid the foundation for his study of free oscillations of the Earth for which he was perhaps best known [Gilbert, 2004]. He further studied pulse propagation and inverse problems in sonar sounding and was promoted to associate geophysicist in 1936. From 1941-1945 Pekeris worked for the Division of War Research at the Hudson Laboratories of Columbia University, again studying the propagation of acoustic pulses and waves; he continued there as director of the Mathematical Physics Group (1945-1950), and had a joint appointment at the Institute for Advanced Study at Princeton. For his war research he was given the title of honorary admiral [Gilbert, 2004].

After the war Pekeris continued his scientific research in several areas, including microwaves, atomic physics, and explosive sound propagation through a fluid-fluid interface, which led to a seminal paper on normal modes and dispersion. He also produced the first theoretical derivation for the critical Reynolds number for onset of instability in pipe flow [Gilbert, 2004].

In addition to his scientific work, Pekeris was involved with assisting in the "birth" and stability of the new state of Israel by aiding in the the transfer of U.S. military surplus to Palestine [Gilbert, 2004]. In 1950, Chaim Weizmann, the first President of Israel, convinced Pekeris to move to the Weizmann Institute of Science in Rehovot Israel to be the founding chair of the Department of Applied Mathematics.

At that time conditions for the university in Rehovot were extreme since Israel was in an almost constant state of war with the students and many faculty in the army. The situation likely contributed to Pekeris' pragmatic approach of pursuing development of applied math and physics through a computational effort [Gillis, 1995]. Thus, part of his negotiation to come the Weizman Institute was to be given funds to build one of the worlds first digital computers for scientific studies, the WEIZAC (Weizmann Automatic Computer), which was completed in 1955 and whose design was based on the von Neumann machine. The WEIZAC's first use was to solve Laplace's equations for Earth's ocean tides for realistic continental boundaries; this was a major accomplishment showing the power of computers to turn theory into "modeling" [Gillis, 1995].

Pekeris continued to build and recruit for the Applied Mathematics department and mentored many grad students who went on in science and other faculty positions. He was also involved in establishing the first Israeli geophysical survey which led to the discover of oil in Israeli territory. In 1952, he was elected to the U.S. National Academy of Sciences. While in Israel he continued to work on atomic physics (on the ground states of helium) as well as wave propagation and and free oscillations in both stars and the Earth, and he was able to test his free-oscillations theory with data from the giant 1960 Chile earthquake. He and his students continued development of computing synthetic seismograms from generalized ray theory, which was computationally intensive and required a computing upgrade from WEIZAC to the more powerful GOLEM series of Israeli-developed "super computers". He continued to work on all these problems of atomic physics, seismology, tides, free oscillations, and hydrodynamics until his retirement at the age of 65 in 1973, which was also the year that his wife Leah passed away. Even after retirement he continued to do research, for example publishing again on the physics of ocean tides in 1978. Near and during this post-retirement time he was recognized for his life-long contributions and was elected to various societies and given prizes such as the Vetlesen Prize (1973), the Gold Medal from the Royal Astronomical Society (1980) and the Israel Prize (1981). In 1990, the Mathematical Geophysics meeting was held in Jerusalem in honor of Pekeris and his contributions. In February of 1993 Chaim Pekeris died as a result of injuries from a fall in his home in Rehovot. The following year the Weizmann Institute of Science began the annual Pekeris Memorial Lecture.

Pekeris' model of mantle convection. Chaim Pekeris's paper on the viability of mantle convection [Pekeris, 1935] was in many ways one of the first truly sophisticated analyses of mantle convection. His basic hypothesis was to examine the convective circulation caused by lateral thermal gradients associated with the difference between a warm subcontinental mantle and a cooler sub-oceanic mantle, both estimated from crustal thickness and mantle heat production. Pekeris also used Haskell's value for mantle viscosity, and calculated that the convective velocities were of the order of 1 cm/year which is a perfectly plausible tectonic velocity. But Pekeris's theory also laid the groundwork for other effects, including accounting for convection in a deep spherical shell, the effect of convection on distortion of the surface, and the net effect of convective density anomalies and surface deflections on the gravity field, thereby predating modern analysis of geoid and topography by 50 years. Pekeris' paper was published 5 months before Anton Hale's paper, although they were both received at the same time (December 1935) and were similarly communicated by Harold Jeffreys to the Royal Astronomical society. As with Hales, Pekeris was not to examine mantle dynamics again since it is likely that this field was perceived as too speculative and without promise.

Further reading, including sources for this brief history are Gilbert [2004] and Gillis [1995].

7.01.2.6 Harry Hammond Hess (1906-1969)

Harry Hess was one of the giants of the plate-tectonics revolution, not only through his legacy of careful sea-going observations, but in his landmark paper [Hess, 1962] hypothesizing the essence of sea floor spreading and subduction. Hess was also (along with Keith Runcorn; see Section 7.01.2.7) one of the leading proponents, at the dawn of the plate tectonics revolution, for the mantle-convection driving mechanism of plate motion.

Harry Hammond Hess was born in New York City in May 1906. At the age of 17 he entered Yale University to study electrical engineering, but switched to Geology and, despite purported failures at mineralogy, graduated with a B.S. in 1927.

After graduating from Yale he worked as a mineral prospector in Northern Rhodesia for two years. He then returned to the U.S. where he started graduate school at Princeton. For his Ph.D. he worked on ultra-mafic peridotite, thought to be part of the mantle. During graduate school he also took part in some of F.A. Vening Meinesz's submarine gravity surveys, particularly of the West Indies island arc, which later inspired him for further marine surveys while in the Navy. Hess finished his graduate studies and received his Ph.D. in 1932. After graduation and brief appointments at Rutgers and the Geophysical Laboratory at Carnegie, he returned to Princeton where he joined the faculty in 1934 and was to remain there for the rest of his life, other than brief visiting professorships at the University of Capetown from 1949-50 (where he likely interacted with Anton Hales), and Cambridge in 1965.

To continue the submarine activities he started with Vening Meinesz, Hess arranged in the 1930s a commission as an officer (lieutenant) in the U.S. Navy reserve. After the attack on Pearl Harbor in December of 1941 he was called to active duty. He was first involved with enemy submarine detection in the North Atlantic and developed a technique for locating German submarines. He volunteered for hazardous duty to complete the submarine detection program by joining the submarine decoy vessel U.S.S. Big Horn. He was later made commanding officer of the U.S.S. Cape Johnson which was a transport ship. Hess was involved with some of the major island-hopping landings of the Pacific theater, such as the landings at the Marianas, Leyte, Linguayan and Iwo Jima. However, Hess also continuously ran the sonar echo sounder to detect bathymetry en route to these landings, thereby collecting seafloor profiles all across the North Pacific. These surreptitious surveys led to the discovery of "guyots", flat topped seamounts, which Hess named after Swiss geographer Arnold Guyot who founded the Princeton department. Hess inferred these guyots to be islands that had been eroded to sea level but fallen below sea level due to seafloor migration, hence providing one of the first major clues of seafloor mobility. Such sea floor mapping continued under the newly formed Office of Naval Research, and this led to the discovery of the mid-ocean ridge system, which was also found to have in many instances rift-shaped valleys running along its length.

After the war Hess returned to Princeton and initiated and directed the massive multi-national Princeton Caribbean Research Project which set out to perform a comprehensive exploration of Caribbean geology, producing more than 30 Ph.D.s in the process. Hess was made department chair in 1950, a position he kept for 16 years, and during which he led a large

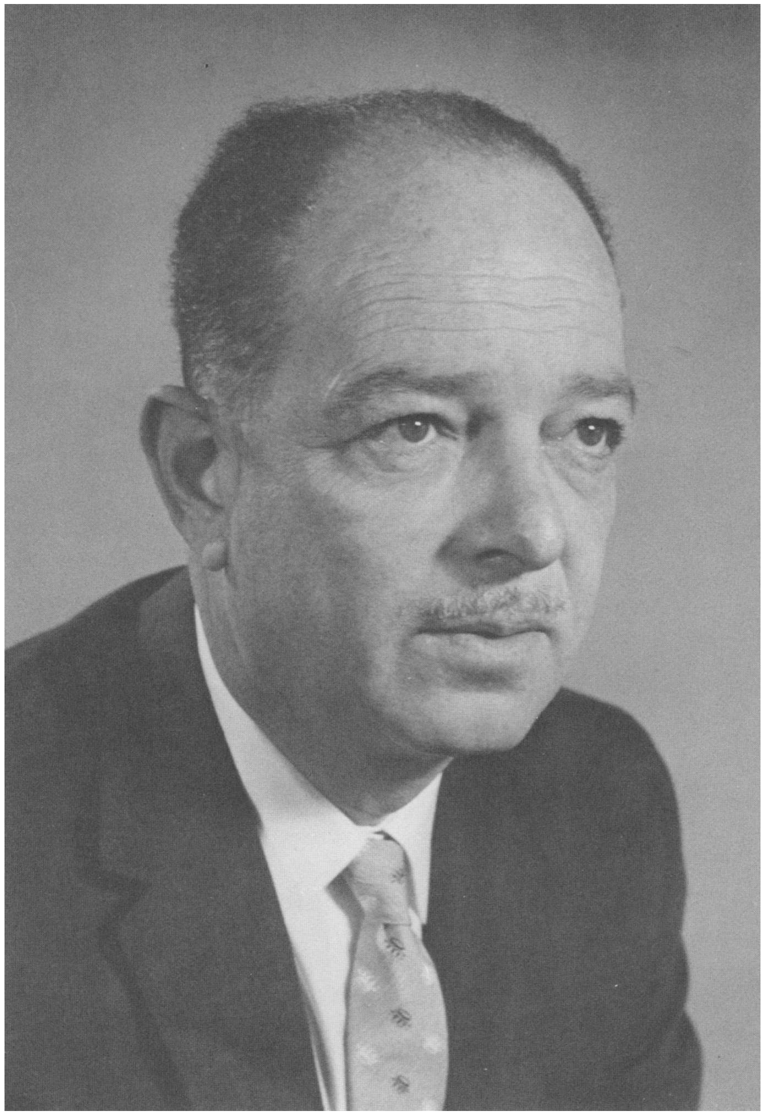

Figure 7: Harry H. Hess (1906-1969). From Shagham et al. (eds.) (1973), *Studies in Earth and Space Sciences: A Memoir in Honor of Harry Hammond Hess*, The Geological Society of America Memoir 132, Boulder, CO: The Geological Society of America.

expansion of the Princeton department. In 1952 he was elected to the National Academy (the same year as Chaim Pekeris' election) and also served on various national advising committees. In the late 1950s he and Walter Munk initiated the Mohole Project to drill through the ocean crust into the mantle, where he continued his work on Mohole through to 1966, leading to technical breakthroughs that paved the way for the Deep Sea Drilling Project.

Harry Hess continued to serve his department and as national adviser through the 1960s. He was involved with development of the national space program and was on a special panel appointed to analyze rock samples brought back from the moon by Apollo 11. He received numerous honors and awards: apart from National Academy membership, he also was given the Penrose Medal in 1966, elected to the American Academy of Arts and Sciences in 1968, and in 1969, just months before his death, he was given an honorary doctorate by Yale.

In late August, 1969, Hess was chairing a meeting of the Space Science Board of the National Academy in Woods Hole Massachusetts, which was discussing the scientific objectives of lunar exploration only a month since the amazingly successful Apollo 11 mission. During the meeting on August 25, Hess suffered a fatal heart attack. He was buried in Arlington National Cemetery. He was posthumously given the NASA Distinguished Public Service award, and the AGU established, as one of its primary awards, the Hess medal in his honor [Leitch, 1978; Dunn, 1984].

Hess, plate tectonics and mantle convection. In 1960 Harry Hess wrote an internal report to the Office of Naval Research propounding his hypothesis of seafloor spreading. Years of experience in seafloor surveying led him to believe that mid-ocean ridges had rift valleys; his knowledge of sedimentology and petrology also made evident to him that neither seafloor sediments nor fossils were ever more than a few hundred millions years old. Hess, was essentially convinced by Wegener's observations of continental breakup, and he proposed the idea that the ocean crust diverged away from linear ridges of volcanic activity, later known as seafloor spreading, and that sediments were swept into trenches. He also proposed that ocean crust was subducted, but continental crust tended to scrape off sea sediments to make mountain ranges. In 1962, Hess republished the same paper in a peer reviewed volume [Hess, 1962], and this paper became one of the most famous and highly cited papers in geoscience, and was a landmark in the plate tectonics revolution. However, evidence and verification of the idea did not come until the Vine-Matthews study of magnetic seafloor lineations in 1963. The idea that the seafloor traveled like a conveyor belt essentially satisfied the main objections to continental drift.

At the same time that Hess proposed sea floor spreading he also concluded, in the same paper, that the driving mechanism for the surface motion was mantle convection, based on observations of gravity anomalies and studies of peridotites, which being ultramafic were assumed to upwell from the mantle. His convection postulate was not based on fluid dynamical analysis but on a synthesis of observations and physical intuition about the ramifications of seafloor spreading and seafloor destruction at trenches. His intuition about the importance of subduction as convection was largely correct, although he, like Holmes, assumed that ridges involved active upwelling (which he also thought carried much more water than is presently known to occur) and that ridges were hence pried apart by convection [Hess, 1962].

Additional reading and historical sources for this brief history are Buddington [1973] Leitch [1978] and Dunn [1984].

7.01.2.7 Stanley Keith Runcorn 1922-1995

Keith Runcorn is a unique figure in that he was at the forefront of major discoveries in paleomagnetism that led to the modern theory of plate tectonics, and was also an early and vigorous proponent for the theory of mantle convection, not just as a driving mechanism for continental drift, but also in other planets, particularly the Moon.

Stanley Keith Runcorn was born in Lancashire, England in November 1922 and was educated there as a youth. While an intellectually active young man, he was more interested in history and geography, although he was eventually persuaded by his father and school headmaster to pursue science, particularly astronomy [Collinson, 1998]. At 18, in 1940, he went to Cambridge to study electrical engineering and graduated in 1943. He subsequently joined a telecommunications research firm in Worcestershire

Figure 8: S. Keith Runcorn (1922-1995). American Geophysical Union, courtesy, AIP Emilio Segre Visual Archives.

to work on radar during the remainder of World War II.

After the war, in 1946, Runcorn took an Assistant Lectureship in Physics at Manchester University to initially work on cosmic radiation, but then moved to study stellar and planetary magnetic fields. The first dynamo theories by Elsasser and Bullard had just been proposed, and Runcorn's first work was to test the core-origin of the geomagnetic field by examining the variation of horizontal field strength in coal mines, which he found to increase with depth thereby lending support to the core origin of the field; this work led to Runcorn's Ph.D. degree in 1949 (see Collinson [1998]).

In 1950 Runcorn moved to the Cambridge Department of Geodesy and Geophysics and worked on remanent magnetism of rocks of different ages to infer polar wander paths for both Great Britain and North America which were found to differ. After testing and eliminating the possibility of large uncertainty in the data, Runcorn became convinced that the variation in paths was due to continental drift, and this set of observations in the end formed one of the cornerstones for the advent of plate tectonics. (See [Girdler, 1998].)

In 1956, Runcorn left Cambridge for the Chair of Physics at King's College, University of Durham at Newcastle upon Tyne. He was to remain there until his retirement from the British system in 1988. He quickly established a geophysics program within the Physics Department (largely by moving Cambridge colleagues with him) and continued to work on and foster paleomagnetic studies, with considerable field work of his own in the Western United States. In this time he also established his well known reputation for extensive travel and departmental absence, earning the facetious title of “Theoretical Professor of Physics” [Collinson, 1998].

It was during his time in Newcastle that Runcorn began his work on mantle convection (see below), which also led to his growing core hypothesis that had implications for the change of length of day. These ideas prompted Runcorn to move toward the study of coral growth rings, which demonstrated that he had no fear of moving into a different field, even if it was biology. He also continued work through the 1960s on ocean currents and tides, but then eventually landed on the study of the Moon which, given the advent of space exploration and the Apollo program, was a field he would pursue for the remainder of his life. Runcorn continued to work on ideas of convection and geomagnetism in the Moon as well as on various other topics including Chandler Wobble, Jupiter's rotation, and Mars geodesy. In the late 1980s, before his retirement, he also became interested in variations in the gravitational constant G, but this pursuit was eventually found to be fruitless. Runcorn retired from Newcastle in 1988 and took a part-time Chair at the University of Alaska at Fairbanks, while also keeping a position in Physics at Imperial College London. During his life, Runcorn had been elected a Fellow of the Royal Society (1965), received the Gold Medal of the Royal Astronomical Society (1984), the Fleming Medal of the AGU (1983), Vetlesen Prize (1971), Wegener Medal (1987), and several other honors.

In 1995, on the way to the AGU meeting in San Francisco, Keith Runcorn stopped off in San Diego to give a seminar and discuss Galileo Orbiter results with a colleague. On December 5, he was found dead, the victim of a violent homicide, the perpetrator of which was later apprehended and found guilty of first degree murder and sentenced to imprisonment [Imperial College Reporter, 1996; Nature, 1997].

Runcorn and mantle convection. Not long after his move to Cambridge in 1956, Keith Runcorn became interested in mantle convection as a driving mechanism for continental drift. In two papers in Nature in 1962, [Runcorn, 1962b,a], he established the theoretical arguments for subsolidus creep in the mantle under buoyancy stresses and made a quantitative prediction of convective velocities similar (although perhaps unbeknownst to him) to those of Hales and Pekeris. He also believed that a growing core influenced the onset of convective-driven drift, an idea that never found much traction.

Runcorn also proposed the then radical idea that the long wavelength geoid was not frozen into the Earth but due to mantle convection [Runcorn, 1963]. While Runcorn's analysis of the geoid was not as sophisticated as modern analysis (see Ch.2,4 and 8 this volume), it did lead him to infer that spreading centers were not sites of deep active upwellings, as had been inferred by Holmes and Hess, but were better explained by broad upwellings, which is a more modern and plausible view of mantle flow (see Ch.7 this volume; Forsyth Vol.1). This observation also prompted Runcorn to have little faith in the significance of the ridge-push force [Runcorn, 1974; Girdler, 1998]. In many ways, Keith Runcorn's views of mantle convection were well ahead of their time and have largely been born out by the last several decades of analysis.

Additional reading and historical sources for this brief history are Collinson [1998] and Girdler [1998].

7.01.2.8 Mantle convection theory in the last 40 years

The origin of modern mantle convection theory was not only contemporaneous with the birth (or rebirth) of the theory of plate tectonics but also with the advent of the study of nonlinear convection. Up till the early 1960s, the study of linear convection, i.e., the onset of convective instability from infinitesimal perturbations (see Ch.2 and 4 this volume) was well studied across several fields, as summarized in the classic treatise by Subramanyan Chandrasekhar (1910-1995; Nobel Prize 1983) [Chandrasekhar, 1961]. However, the mid 1960s witnessed increased activity in experimental studies of convection as well in theories of finite-amplitude or nonlinear convection [see Manneville, 2006]. Well controlled experiments that documented transitions in convective state (e.g., patterns) (see Ch.3 this volume) provided inspiration and testing for various studies of nonlinear convection, leading to several seminal theoretical approaches such as nonlinear perturbation theory and matched asymptotic analysis (see Ch.4 this volume).

Along with the plate tectonics revolution and the renewed study of the physics of convection, mantle convection theory made rapid progress and growth and achieved a rather mature level in the late 1960s and early 1970s [e.g., Turcotte and Oxburgh, 1972; Oxburgh and Turcotte, 1978] through the work of various investigators that had migrated in from physics and engineering, mostly notably Dan McKenzie, Jason Morgan, Donald Turcotte and Gerald Schubert, the former two also having made major contributions to formulating the modern working theory of plate tectonics (see Wessel, Vol.6.). Throughout the late 1960s and 1970s, many of the fundamental problems of convection in a solid-state mantle had been identified, although not necessarily solved. This included the fact that mantle convection was occurring in a fluid with a complex variable rheology, and that convection was occurring through multiple solid-solid phase transformations most notably at the top and bottom of the Earth's transition zone at depths of 410 km and 660 km, respectively (see Kind Vol.1, Oganov Vol.2 Ch.2 and Ch.8 this volume). This work set the stage for the explosion in the field of mantle dynamics that occurred during rapid improvements in computing power and numerical methods. In particular, many seminal contributions in the numerical analysis of mantle convection were made by Ulrich Christensen and colleagues during the 1980s and 1990s. With the combination of laboratory, theoretical and numerical analyses, along with improved observations coming from, in particular, seismology, isotope geochemistry, and mineral physics, our picture of mantle convection has progressed in the last 20 years to highly sophisticated levels of complexity and realism, although much still remains to be understood.

7.01.3 Observations and evidence for mantle convection

Many of the observations that are relevant to mantle dynamics are covered in other volumes of this treatise, as well as within this volume. As discussed above in Section 7.01.2, the modern theory of mantle convection was motivated as the driving mechanism for continental drift and plate tectonics. The observations that in themselves inspired the resurgence of the mobile-surface theory of plate tectonics was largely from paleomagnetic studies showing relative continental motion and seafloor spreading (see Sections 7.01.2.6, 7.01.2.7, and Kent Vol.5, Wessel Vol.6). Global seismicity also gave clear delineation of the structure of plates and locations of plate boundaries (Ekstrom Vol.4) as well as outlines of subducting slabs along zones of deep earthquakes or Wadati-Benioff zones (Houston Vol.4). With the advent of the space program and satellite measurements came accurate geodetic measurements of sea-surface height and hence global models of the Earth's geoid and gravity field (Jekeli Vol3) which provide important constraints about the density structure of the mantle associated with convection (see Forte, Vol.1).

Mantle geochemistry and petrology also provided important constraints on mantle dynamics through the analysis of magma reaching the surface from the mantle at mid-ocean ridges, ocean-islands, large igneous provinces, and at subduction-related arcs. Isotopic and petrologic analyses of melting as well as melt fractionation of trace elements gave important information regarding the depth of melting beneath ridges and hotspots. However, the disparity between the concentration of incompatible elements in mid-ocean ridge basalts (MORB) and ocean island basalts (OIB), in addition to a host of other geochemical arguments involving, for example, noble gas isotopes, has been one of the driving motivations for inferences about the preservation of isolated reservoirs (e.g., layering) in the mantle. These geochemical observations, however, seem to conflict with geophysical evidence for whole-mantle stirring by sinking slabs [van der Hilst et al., 1997; Grand et al., 1997] and this has engendered a long standing debate about the structure and nature of mantle convection (see Section 7.01.6.2, Ch.10 this volume, and Wood Vol.2).

Our understanding of mantle dynamics also draws from observations on other planets. The lack of cratering record on Venus argues for massive resurfacing events, and giant volcanoes on Mars are evidence of extensive and deep magmatism (see chapters by Ivanov and Breuer Vol.10). However, that neither of our neighboring terrestrial planets appears to have at least present-day plate tectonics continues to be one of the corner-stones in the argument that plate tectonics requires liquid water [Tozer, 1985].

7.01.4 Mantle properties

The study of mantle convection has a boundless appetite for information on the properties of the convecting medium. Indeed, what caused the theory of continental drift to be marginalized for decades was the material property argument by Sir Harold Jeffreys that the Earth was too strong to permit movement of continents through ocean crust. Later measurements of mantle viscosity by postglacial rebound were an important key element in recognizing that the mantle is fluid on long time scales (see Ch.2).

Fluid dynamics is rife with dimensionless numbers and one of the most important such numbers in the study of convection is the Rayleigh number (see Ch.2 this volume). The Rayleigh number defines the vigor of convection in terms of the competition between gravitationally induced thermal buoyancy that acts to drive convective flow, and the dissipative or resistive effects of both fluid viscosity, which retards convective motion, and thermal diffusion which acts to diminish thermal anomalies. The Rayleigh number is written generically as

$$Ra = \frac{\rho g \alpha \Delta T d^3}{\kappa \mu} \tag{1}$$

where ρ is density, g is gravitational acceleration, α is the thermal expansivity, ΔT is the typical temperature contrast from the hottest to coldest parts of the fluid layer, d is the dimension of the layer such as the layer thickness, κ is thermal diffusivity and μ is dynamic viscosity (again, see Ch.2 this volume).

Estimate of the mantle Rayleigh number by itself requires knowledge of the material responses to various inputs such as heat and stress. The response to heat input involves heat capacity, thermal expansivity α, and heat conduction or thermal diffusion (κ) (Oganov Vol.2; Hoffmeister Vol.2; Ch.2 this volume). The density structure inferred from high pressure and temperature experiments (Oganov Vol.2), and and seismology (Dziewonski Vol.1 and Kind Vol.1) constrain how mantle density ρ responds to pressure changes as upwellings and downwellings traverse the mantle, undergoing simple compression or decompression as well as solid-solid phase transitions; both effects can have either stabilizing or destabilizing effects on mantle currents (Chapters 2, 8, and 9 of this volume).

One of most important factors within the Rayleigh number and in the overall study of mantle convection is viscosity μ. That the mantle is viscous at all was one of the key elements in determining the viability of the mantle convection hypothesis. That continents were inferred to be in isostatic balance clearly implied that they are floating in a fluid mantle; but isostatic equilibrium does not indicate how fluid the mantle is since it gives no information about how long it takes for the floating continents to reach an isostatic state. However, measurements of this approach to isostasy could be taken by examining post-glacial rebound, i.e., the uplift of high-latitude continental masses such as Scandinavia and Canada, following the melting of the glacial ice caps after the end of the last ice age (Haskell [1937]; see Mitrovica Vol.3). From these analyses came one of the most crucial and well-known material properties: the average viscosity of the mantle of $\mu = 10^{21}\mathrm{Pa\ s}$. Today, the analysis of the mantle's response to changing loads (e.g., melting ice caps or a decrease in Earth's rotation rate) is done through an increasingly sophisticated combination of geodetic satellite and field analyses, which further refine the viscosity structure of the mantle (Mitrovica Vol.3; Forte Vol.1; Chapter 2 and 4 this volume).

The viscosity of the mantle is so large that it is called a slowly moving or creeping fluid and thus does not suffer the complexities of classical turbulence (Ch.2 this volume). However, one of the greatest of all complexities in mantle dynamics is associated with the various exotic rheological behaviors of mantle rocks, which are almost exclusively inferred from laboratory experiments (Kohlstedt Vol.2). Mantle viscosity is well known to be a strong function of temperature, and the dramatic increase in viscosity toward the surface leads to various conundra about how plate tectonics forms or functions at all and/or how subduction zones can ever initiate from such a cold strong lithosphere (Chapters 2, 3 and 8 this volume; Kohlstedt Vol.2; Sleep Vol.9). The mantle's rheology is also complicated by the various deformation mechanisms it can assume, prevalently diffusion creep at "low" stress, and dislocation creep at higher stress, although other creep and slip mechanisms are also possible (Kohlstedt Vol.2; Ch.2 this volume). In diffusion creep, viscosity is a function of mineral grainsize and this effect can induce dramatic changes if grain-growth or grain-reduction mechanisms exist. In dislocation creep viscosity is non-Newtonian and is a function of stress itself, thereby undergoing pseudo-plastic behavior in which the material softens the faster it is deformed. These and many more complexities (see below in Section 7.01.6.4) continue to keep mantle convection a rich field.

7.01.5 Questions about mantle convection we have probably answered

7.01.5.1 Does the mantle convect?

It seems the existence of this entire volume as well as an enormous body of literature on mantle convection seems to obviate this question. However, we should understand that the notion that the mantle convects was not entirely accepted less than 50 years ago. The physical requirements or conditions for a fluid mantle to convect (i.e., a sufficiently high Rayleigh number) could be inferred from material property measurements; these indeed imply that the Rayleigh number is perhaps a million times what is needed to just barely convect at all, and thus should be convecting vigorously (Ch.2, this volume).

But the direct observation of a convecting mantle is most closely linked to those that verify plate tectonics (Kent Vol.5) and to seismic imaging of the

Earth's interior. Plate spreading and subduction, and the "creation" and "destruction" cycle of lithosphere that they represent, demand vertical transfer from the surface into the mantle and vice versa. That heat-flow and bathymetry measurements show the lithosphere going from a hot ridge to a cold trench is not only evidence that ridges and trenches are the expression of upwellings and downwellings, respectively, but that the cooling lithosphere is nothing more than a convective thermal boundary layer (Ch.2, 4; Jaupart Vol.6). Lastly, seismology has not only given us the deep-earthquake trace of a the cold sinking slab along the Wadati-Benioff zone (Houston, Vol.4) but also tomographic images of these same slabs sinking deep into the mantle [van der Hilst et al., 1997; Grand et al., 1997]. There remains little if any doubt that the mantle convects, but it is important to remember what the first order evidence is for this conclusion, especially considering that the mantle is more inaccessible to direct observation than distant galaxies.

7.01.5.2 Is the mantle layered at 660 km?

The average structure of the mantle in terms of density and elastic properties was shown by seismological studies (augmented by mineral physics) to contain discontinuities, most notably at about 410 km and 660 km depths (Dziewonski Vol.1; Kind, Vol.1; Oganov Vol.2), the latter one being considerably more distinct. The presence of a strong discontinuity in density at 660 km depth suggested that the lower mantle was a denser and perhaps isolated and sluggish layer convecting separately from the upper mantle. This layered-convection argument was reinforced by observations that deep earthquakes along subducting slabs seem to cease around 700 km down (Houston Vol.4), and that some tomographic images show slabs stalling at this depth. This view also fit well with the geochemical inferences that mid-ocean ridge basalts and ocean-island basalts must be coming from different layers (the former from the upper mantle above 660 km, the latter from the lower mantle below 660 km; see also Section 7.01.6.2 and Ch.10 this volume). The convergence of seismology and geochemistry toward a single model of a mantle layered into compositionally distinct regions was indeed a compelling argument. The prospect of mantle convection existing in two layers separated at 660 km depth was a prevalent theme in the study of mantle convection for several decades starting in the late 1960s.

However, high-pressure mineral physics experiments indicated that mantle discontinuities are most likely associated with solid-solid phase transitions, not compositional changes. The major upper mantle component olivine was shown to undergo a change to a spinel structure called wadsleyite at 410 km depth; wadsleyite itself undergoes a less dramatic transition to a ringwoodite at around 510 km, and then, at 660 km depth, ringwoodite changes to a combination of perovskite and magnesiowüstite (Oganov Ch.2). Studies of convection in the presence of such phase changes indicated that they might impede convection temporarily but not indefinitely (Chapters 2 and 8 this volume); and indeed seismic tomographic studies using body waves showed that many slabs do indeed penetrate this boundary and sink well into the lower mantle [van der Hilst et al., 1997; Grand et al., 1997].

In the end, the predominant evidence points to the mantle not being layered with an impermeable boundary at 660 km depth. This of course leads to other unsolved conundra, especially with regard to explaining geochemical observations, which has thus inspired several variants of deep mantle layering and ways of isolating reservoirs or chemical components (Ch.10, this volume).

7.01.5.3 What are the driving forces of tectonic plates?

Upon the widespread acceptance of the plate-tectonic model considerable effort was put forward to make

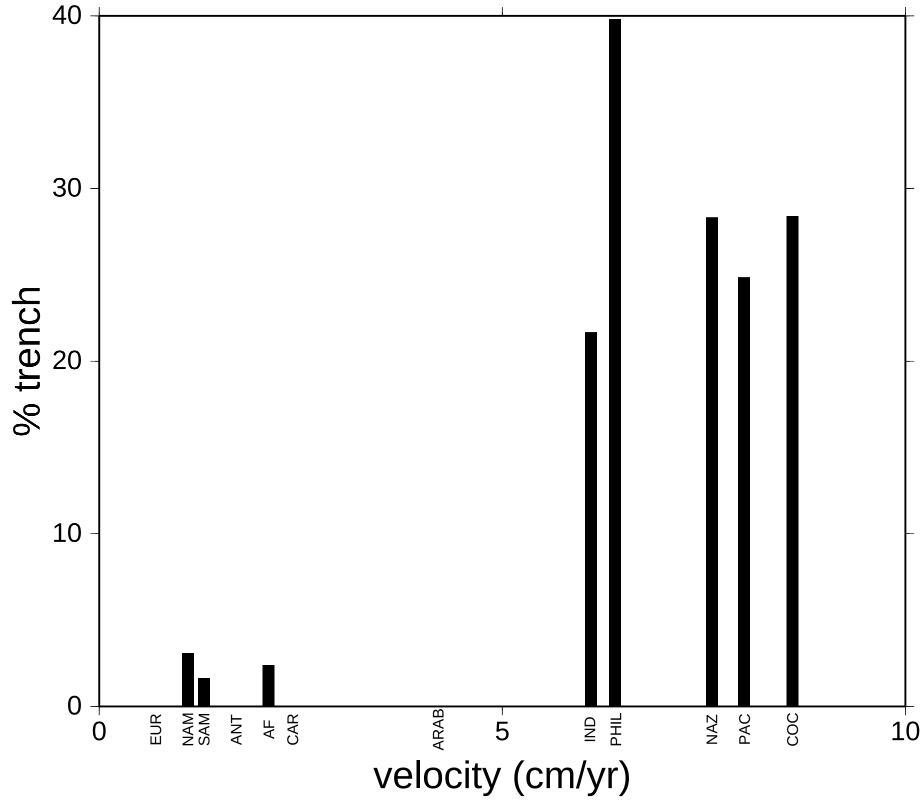

Figure 9: A histogram of percent trench length (percent that a plate boundary is comprised of subduction zone) versus plate velocity for the major plates (initials indicated). (Initials on the abscissa are for European (EUR), N. American (NAM), S. American (SAM), Antarctic (ANT), African (AF), Caribbean (CAR), Arabian (ARAB), Indo-Australian (IND), Phillippine (PHI), Nazca (NAZ), Pacific (PAC) and Cocos (COC) plates.) Adapted from Forsyth and Uyeda [1975] after Bercovici [2003]. Elsevier.

direct estimates of the plate-driving forces. This effort was perhaps best represented by the seminal work of Forsyth and Uyeda [1975], although considerable work has followed since then [Jurdy and Stefanick, 1991, e.g.,]. Several plate forces have been coined, most notably the two driving forces of ridge push and slab pull. Which of these two forces is dominant was the subject of some debate [Hager and O'Connell, 1981; Jurdy and Stefanick, 1991]. However, perhaps the most compelling evidence for slab pull is the profound correlation, shown in the original paper of Forsyth and Uyeda [1975], between the fraction of convergent (trench) boundary and plate velocity (Figure 9); essentially no other meaningful correlation was shown between any other type of boundary and plate velocity. This correlation showed that the fastest plates (of order 10 cm/yr) have the most amount of slab connected to them, while the slowest plates (of order 1 cm/yr) have little or no slab connected to them. This demonstrated rather conclusively that slab pull is the driving force of plate tectonics, because quite simply, for a plate to move it needs a slab (see Ch.8 this volume). What is also important about this inference from a mantle convection perspective is that it fits very well with the modern picture of cold downwelling or slab dominated mantle circulation. That is, the Earth's mantle is primarily driven by the surface cooling of a mantle that is more or less uniformaly heated by radioactive decay of uranium, thorium and (at one time) potassium, and is also losing primordial or fossil heat (Ch. 5 this volume); such a configuration of distributed heat production and surface heat loss typically leads to convection dominated by cold downwelling currents, which are synonymous with subducting slabs (see Chapters 2 and 8 this volume). Most importantly of all, the estimate of plate-driving forces are thus completely reconcilable with and even subsumed by the theory of mantle convection. Moreover, this inference leads to the important conclusion that the tectonic plates are not so much driven by convection, they *are* convection. The plates are cooling thermal boundary layers that are both driven by and become slabs, which are in themselves convective downwellings; the plates are thus convection.

7.01.6 Major unsolved issues in mantle dynamics

7.01.6.1 Energy sources for mantle convection

The discovery of radioactive elements at the turn of the 19th century was a key discovery in many regards, including providing evidence that the Earth has internal sources of heat. This was also the key argument to refute Lord Kelvin's estimate for the age of the Earth since he assumed it was cooling freely (without heat sources) from an initially molten state (see above Section 7.01.2.4 and also Stevenson Vol.9). Early estimates of the concentration of radioactive elements inside the Earth are based on heatflow and geochemical measurements of crustal rocks, in conjunction with cooling models (Ch.5 this volume); these arguments tended to point toward a high enough concentration of radioactive elements in the mantle to account for as much as 70-80% of the heatflow out of the Earth to be due to radiogenic heating [Schubert et al., 2001]. This satisfied the condition that the Earth has been cooling relatively slowly over its 4.5 Gyr lifetime. However, recent estimates of radioactive element abundances from the study of chondrites (thought to be representative of planetary building blocks) possibly suggest somewhat less radiogenic heating (see Ch.5 this volume). If radiogenic heating is small, then more of the Earth's heatflow is from loss of fossil heat (as with Lord Kelvin's assumptions; see also England et al. [2007]); this would demand rapid cooling from a recently excessively hot or even molten state, unless the physical process of convection was itself somehow very different in the past in order for the mantle to retain its heat (see Ch.5, this volume, and Sleep Vol.10). Alternatively, if chondritic estimates of these radiogenic sources are very wrong, then it implies significant problems with the chondritic model for planetary composition and thus for our understanding of Earth's formation. Either possibility leads to many intriguing directions for future inquiry.

7.01.6.2 Is the mantle well mixed, layered, or plum-pudding?

As mentioned above in Sections 7.01.3 and 7.01.5.2 there are various lines of geochemical evidence – ranging from the disparity between trace element abundances in mid-ocean ridge basalts and those in ocean-island basalts, sources and reservoirs of noble gases, source and origin of continental crust, etc. – that suggest that the mantle has isolated reservoirs, such as distinct layers. Although layering of the mantle at 660 km depth has probably been eliminated, the motivation still persists to reconcile the geochemical inference of an unmixed mantle with the geophysical evidence of a well-stirred mantle. The problem remains unsolved, although various models and solutions have been proposed, in particular deep layering, or mechanisms for keeping the mantle poorly mixed (the "plum-pudding" model). This issue comprises the major thrust of Chapter 10 (this volume), and is touched upon in Ch.9 as well as in other volumes, notably Wood Vol.2.

7.01.6.3 Are there plumes?

Convective plumes are relatively narrow cylindrical upwellings typical of convection and especially in fluids with strongly temperature-dependent viscosity, such as mantle rocks. The existence of plumes in the mantle was proposed by Jason Morgan (see Ch.9 this volume) to explain anomalous intraplate volcanism such as at Hawaii. That hotspots appeared to be more or less immobile relative to plates suggested a deep origin, and it has often been supposed that plumes emanate from the most obvious heated boundary in the mantle, the core-mantle boundary. However, plumes have eluded direct observation by seismic methods, other than with recent fore-front techniques that still remain controversial [Montelli et al., 2004]. To some extent, evidence for the existence of plumes is still circumstantial and thus they remain the subject of ongoing debate. The subject of plumes and melting anomalies is discussed in Chapter 9 of this volume.

7.01.6.4 Origin and cause of plate tectonics

As noted already, the modern theory of mantle convection was motivated to provide the driving mechanism for plate tectonics. We also argued above (Section 7.01.5.3) that plate tectonics is indeed convection. However, there still remains no unified theory of mantle dynamics and plate tectonics, wherein plate tectonics arises naturally and self-consistently from mantle convection. There are some aspects of plate tectonics that are reasonably well explained by convective theory, in particular the existence of cold planar downwellings akin to subducting slabs (Ch.8 this volume). But still many first order questions remain. Just with regard to subduction itself, there is still no widely accepted theory of how a subduction zone and sinking slab initiates from a thick cold and, by all appearances, immobile lithosphere (Chapters 2, 3 and 8 this volume); lithospheric instabilities and sub-lithospheric small-scale convection are easily generated (Ch.7 this volume), but a widely accepted mechanism for getting the entire stiff cold lithosphere (from surface to base) to bend and sink remains elusive. Also, asymmetric subduction (only one plate subducts at a trench) is not easily obtained with convection theory, although such asymmetries are likely associated with disparity between oceanic and continental lithosphere.

But many other issues remain in the problem of "plate generation". Although mid-ocean ridges are associated with upwelling from the mantle, all evidence points to the upwelling being shallow and the spreading being passive; i.e., ridges are pulled apart by slabs at a distance, rather than pried apart by a deep upwelling (Forsyth, Vol.1, Lin, Vol.6; Ch.7 this volume). How such passive upwelling occurs in a convection calculation is not universally understood, although self-consistent convection calculations with near-surface melting do a reasonably good job of predicting the formation of passive ridges [Tackley, 2000b]; see Figure 10.

One of the long standing problems in understanding the plate-like features of mantle convection is the generation of toroidal motion, which involves strike-slip shear and spin of plates [Hager and O'Connell, 1979; O'Connell et al., 1991; Dumoulin et al., 1998]. Toroidal motion is enigmatic because it is not directly generated by convective forces but must arise by the coupling of buoyancy driven flow and large viscosity variability (Ch.4 this volume). The dependence of toroidal flow on rheological effects also links it closely to the generation of narrow weak plate boundaries separated by broad strong plates. Plate-like toroidal flow and plate-like structures have been shown to both require severe velocity-weakening mechanisms that are well beyond even the reasonably complex viscous creep rheologies typical of the

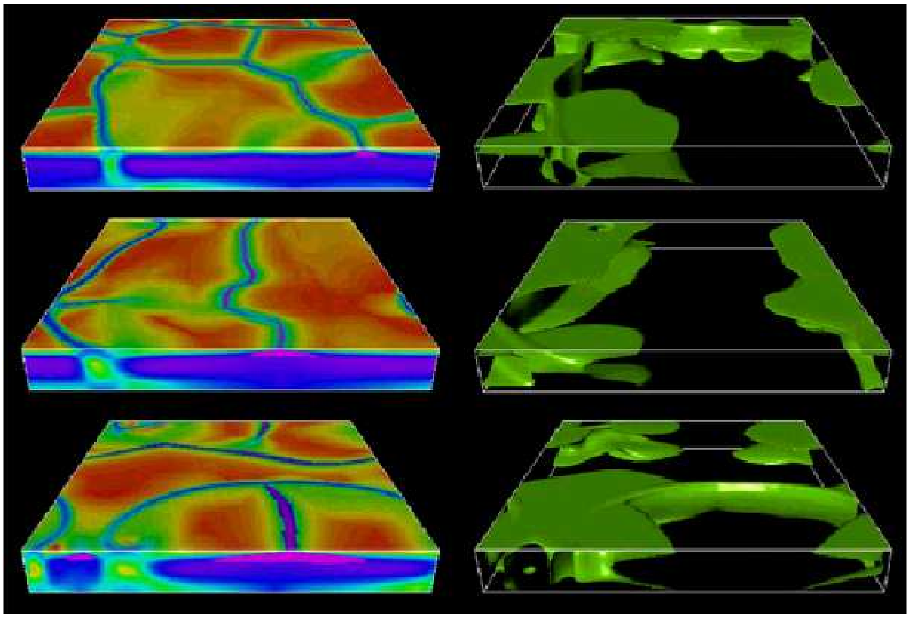

Figure 10: A simulation of plate generation over mantle convection. The plate rheology is visco-plastic and the viscosity reduction associated with melting is parameterized into the model, leading to exceptional plate-like behavior and apparent passive spreading (i.e., narrow spreading centers not associated with any deep upwelling). The right panels show surfaces of constant temperature, which here are dominated by cold downwellings; the left panels show the viscosity field (red being high viscosity and blue low viscosity). Different rows show different times in the simulation. After Tackley [2000b]. American Geophysical Union.

mantle (Figure 11); see for example the review by Bercovici [2003]. The focusing of deformation associated with plate boundary formation and the strike-slip form of toroidal flow are classified as a natural occurrence of shear-localization. Although some creep rheologies (showing plastic behavior) can generate some plausible localization, their effect is instantaneous in that the weak zones only persist as long as they are being deformed, whereas actual plate boundaries have long lives even if inactive and can hence be reactivated [Gurnis et al., 2000]. The mechanisms for such localization are thus likely to involve "state" variables that will grow under a rapidly deforming state, but decay away slowly after deformation ceases. Temperature is a simple analogy of such a state variable in that thermal anomalies can be generated by frictional dissipation and cause weakening, but will diffuse away gradually after forcing stops. More plausible but more exotic shear-localizing state variables might be defect and microcrack density, or as has been proposed by Bercovici and Ricard [2005], the most effective mechanism may be grain-size reduction through damage (Figure 12)

Regardless of their successes, none of these shear-localizing mechanisms have yet to explain the role of water as is assumed to exist (Section 7.01.3). Moreover, essentially all plate generation models have been designed to address present day instantaneous plate motions, and none have even begun to address plate motion changes, and plate growth and shrinkage, although some effort has been made to understand the convective forces that can cause plate motion changes [e.g., Lowman et al., 2003]. Much still remains to be examined in the basic and important problem of plate generation, and aspects of it are discussed throughout this Treatise, in par-

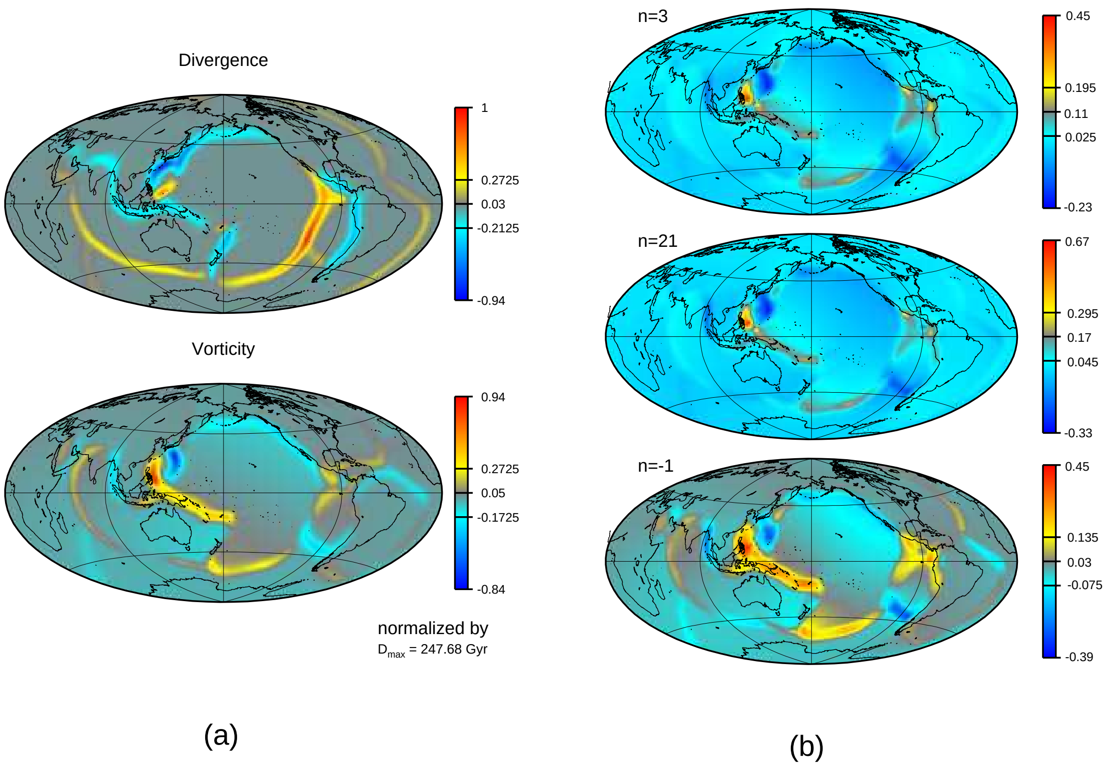

Figure 11: A shallow-layer model mantle-lithosphere flow drives source-sink flow using the Earth's present day divergence field as a source-sink field (upper left); various non-Newtonian rheologies for the lithosphere are examined to see which best recovers the present-day strike-slip or vertical vorticity field (lower left). Power law rheologies are characterized by the power-law index n such that strain-rate goes as stress^n. Positive power indices of $n = 3$ (typical of mantle rocks) or even $n = 21$ (closer to visco-plasticity) are insufficient to recover the vertical vorticity field (upper two right panels). A more exotic rheology with power-law index of $n = -1$, which allows for stick-slip or velocity weakening behavior, is much more successful at reproducing the Earth's vorticity field. From Bercovici [1995]. American Geophysical Union.

ticular Chapters 2, 3, 4, and 8 of this volume, and Sleep Vol.10. Several reviews on plate generation can also be found in the literature, in particular those of Bercovici [2003]; Bercovici et al. [2000]; Tackley [2000a].

7.01.7 Burgeoning and future problems in mantle dynamics

7.01.7.1 Volatile circulation

The interaction of the ocean and atmosphere with the mantle has in fact been an important and fertile field of study for the last few decades, although it has largely been the province of mantle petrology and geochemistry. However, questions of how much the mantle entrains, returns and stores various important

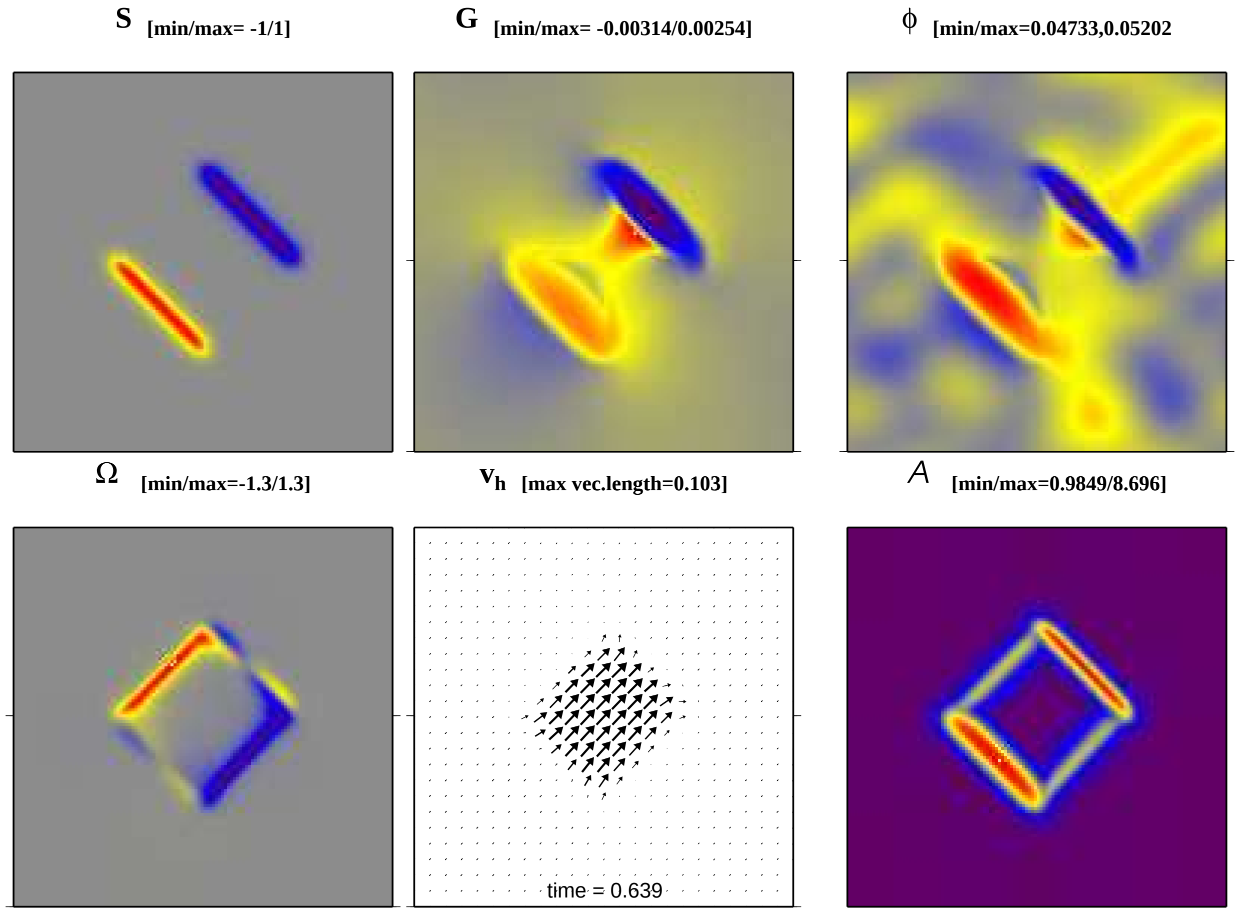

Figure 12: A simple source-sink model of shallow flow with a two-phase and grainsize-reducing damage mechanism. Damage per se involves transfer of deformational work to the creation of surface energy on interfaces by void and/or grain boundary generation in the continuum. In the case shown, all damage is focussed on grainsize reduction. The panel meanings are indicated by symbols where S is the imposed divergence rate (i.e. the source-sink field) that drives flow; G is the dilation rate due to void formation; ϕ is void volume fraction; Ω is vertical vorticity or rate of strike-slip shear; $\mathbf{v_h}$ is horizontal velocity; and $\mathcal{A}$ is the "fineness" or inverse grainsize. This particular calculation shows that fineness-generating, or grainsize reducing, damage is very effective at creating localized fault-like strike-slip zones in vorticity Ω, and solid-body like translation in the velocity field $\mathbf{v_h}$. Adapted from Bercovici and Ricard [2005]. American Geophysical Union.

volatiles such as water and carbon dioxide remain important and largely unanswered [Williams and Hemley, 2001; Karato, 2003; Hirschmann, 2006]. The relevance of the problem is manifold, but can be summarized perhaps in two themes: First, the ingestion of volatiles by the mantle affects its convective circulation and thus both the thermal and chemical evolution of the mantle, mainly because of the rheological effects of volatiles (which tend to weaken rocks) as well as their tendency to facilitate melting and hence chemical and isotopic fractionation. Second, how the mantle ingests, stores and releases various volatiles controls the evolution of the oceans and atmosphere, both in their size (or mass) as well as composition (since difference volatiles are likely to be entrained and stored differently).

The flux of volatiles into the mantle is primarily through subduction zones [Peacock, 1990; Hirschmann, 2006]. Crustal rocks entering a subduction zone are necessarily hydrated by virtue of being submarine. Whether the lithosphere as a whole is hydrated is questionable since it tends to be dried during the process of mantle melting and formation of crust at ridges. Absorption of carbon dioxide is first by dissolution in sea-water to form an acidic solution that reacts with calcium rich sediments to produce carbonates [Falkowski et al., 2000], which are then entrained by subduction. However, the quantification of volatile entrainment through subduction zones is problematic for many reasons; in the case of water it is difficult to make an accurate estimate of how much gets carried by the slab, how much continues to be carried down after devolatilization through arc magmatism, and which hydrous silicate phases in the slab are capable of carrying water to significant mantle depths [Williams and Hemley, 2001; Hirschmann, 2006]; see also Wood Vol.2.

Storage of volatiles in the mantle is also the subject of much debate. Although solid rocks cannot absorb volatiles in great concentrations, the mass of the mantle is so large that it could conceivably hold several to tens of world ocean masses. Moreover, the region of the mantle between the phase transitions at 410 km and 660 km depths – called the transition zone – is known for having anomalous solubility of at least water and while it is only a tenth of the thickness of the mantle it could hold much more water than either the upper mantle (above 410 km) or lower mantle (below 660 km) combined. The transfer of anomalous water from the transition zone through convection could possibly cause deep melting, as has been proposed since the early 1990s [e.g., Inoue and Sawamoto, 1992; Inoue, 1994]; this melting might have an effect on trace-element circulation and led to the appearance of layering in whole-mantle convection [Bercovici and Karato, 2003; Karato et al., 2006]. How much volatile mass is eventually returned to the oceans and atmospheres through volcanism is perhaps better constrained since most non-arc volcanic output occurs at mid-ocean ridges whose basalts are relatively dry. The ingestion of water by slabs and meager water return at ridges suggests that the mantle is on the whole absorbing oceans, although it is equally possible that little water is taken into the mantle beyond arc volcanism [Dixon et al., 2002]; see Ch.8 this volume, Wood Vol.2, and Hirschmann [2006]. The balance of volatiles between the oceans and atmosphere is an ongoing debate since it relies on various feedback mechanism, some of which are still not well articulated. Volatiles will tend to reduce mantle viscosity and enhance convective vigor, but whether this enhances ingestion or output of water is not entirely known and similar models can lead to very different conclusions, such as complete mantle degassing in a brief time [McGovern and Schubert, 1989], or drainage of the oceans into the mantle over billions of years [Bounama et al., 2001]. However, evidence that ocean masses have remained more or less constant over billions of years [see Hirschmann, 2006] implies a steady state exchange of the mantle with the oceans and atmosphere that has either a trivial explanation (i.e., there is no exchange), or requires a self-regulating feedback mechanism. Such mechanisms might involve the ocean-mantle contact area that governs the size (depth and breadth) of the world's oceans, and thus the size of ocean basins, plate boundary lengths and plate sizes. To simply state that the subduction and ridges must ingest and eject an equal amount of water is not an explanation since the mechanisms of absorption at subduction zones and release at ridges are vastly different and it would be fortuitous if they could balance each other for any given plate or ocean-size configuration.

7.01.7.2 Mantle convection, water and life

The presence of liquid water on Earth is likely a necessary condition for plate tectonics, and an obvious necessary condition for the existence of life as we know it. A major question still remains as to whether all three are linked; i.e., that plate tectonics has allowed liquid water and life, or possibly even whether life has influenced plate tectonics. The volcanic return of subducted carbon dioxide, which is removed from the atmosphere by oceans and seafloor sediments, likely sustains a greenhouse state that keeps the surface temperature sufficiently high for water to remain liquid, and hence permit plate tectonics. Moreover, the absorption of carbon dioxide by ocean-sediment reactions, which prohibit buildup of CO_2 and thus a possible runaway greenhouse, is probably also tectonically controlled by the continuous exhumation of calcium rich minerals through mountain building [Walker et al., 1981]. Thus plate tectonics possibly plays a role in keeping the the Earth at the right temperature for liquid water (and life) to exist, and thus for plate tectonics itself to persist [Ward and Brownlee, 2000]. Whether or not life is a mere passive player in this balance remains an open question.

7.01.8 Summary and context of the rest of this volume

This volume on mantle dynamics is designed to follow two themes: (1) how is mantle convection studied, and (2) what do we understand about mantle dynamics to date. The first 4 chapters following this overview are thus concerned with pedagogical reviews of the physics of mantle convection (Ch.2), laboratory studies of the fluid dynamics of convection relevant to the mantle (Ch.3), theoretical analysis of mantle dynamics (Ch.4), and numerical analysis and methods of mantle convection (Ch.5). The subsequent chapters concentrate on leading issues of mantle convection itself, which include the energy budget of the mantle (Ch.6), the upper mantle and lithosphere in and near the spreading center (mid-ocean ridge) environment (Ch.7), the dynamics of subducting slabs (Ch.8), hotspots, melting anomalies and mantle plumes (Ch.9), and lastly geochemical mantle dynamics and mixing (Ch.10).

The physics of mantle convection is extensively multi-disciplinary since it involves not only fluid mechanics, but also gravitational potential theory (to understand not only self-gravitation of our massive convecting medium but how the shape of the geoid or sea-surface is affected by and informs us about convection), seismology and mineral physics (to understand the thermodynamic state and properties of the mantle such as density, thermal expansivity and solid-solid phase transitions), material science (to understand rheology and deformation mechanisms and transport phenomena), and geochemistry, petrology and complex multiphase, multicomponent flows (to understand chemical mixing and mantle melting). Chapter 2 begins by elucidating the basic physics of convection universal to any fluid system, and then proceeds to discuss the complexities associated with the mantle, including, for example, compressibility, phase changes, viscoelasticity, silicate rheology, etc. Many of the future research topics involving mantle complexities cannot be described with single-component and single-phase fluid mechanics, thus some care is given to develop an introduction to complex fluids entailing multicomponent systems undergoing mixing and chemical transport, as well as deformable multiphase media.

As discussed above in Section 7.01.2.3, the initiation of the modern study of convection is attributed to the first systematic experimental studies of Henri Bénard. Thus, Chapter 3 involves a survey of laboratory methods for studying convection, and for approaching the particular complexities of mantle convection itself. Convection in the mantle is, of all geophysical flows, perhaps most easily scaled to laboratory conditions since the ratio of viscosity to the cube of layer thickness is easily preserved between the mantle and the laboratory model. Moreover, laboratory models do not suffer the assumptions made in physical theory to obtain a closed system, the simplifying approximations of analytic theory to obtain a mathematical solution, or the limitations of numerical resolution in computer models; thus the need for studying convection in real materials is paramount. However, the mantle is an exotic fluid in that it is undoubtedly chemically inhomogeneous, has phase changes, is heated and cooled internally, and has rheology sensitive to various state variables such as temperature, pressure and stress or grainsize, and these effects are all difficult to reproduce in the laboratory and with available laboratory fluids. Thus, progress in laboratory models is both vital for exploring new physics and testing theories, but remains an extremely challenging field. Chapter 3 thus not only discusses the methods for creating and observing convection experiments, but also reviews the considerable progress in incorporating the complexities of the mantle itself into these experiments.

The birth of convection as a field of physics is also associated with Lord Rayleigh's seminal theoretical work on convective instability (Section 7.01.2.2). In the last 40-50 years the theoretical analysis of convection in both the linear and especially nonlinear regimes has burgeoned, not only because of its relevance to planetary and stellar atmospheres and interiors, but because convection is the classic paradigm of a nonlinear dynamical system undergoing chaotic behavior and self-organization [e.g., Nicolis, 1995]. Thus Chapter 4 surveys the wealth of theoretical analyses on convection itself, as well as on individual theories relating to features of convective circulation. Thus the initiation of mantle plumes is examined through stability (Rayleigh-Taylor) theory, and fully developed plumes and mantle diapirs through simpler fluid dynamical models. Likewise, subducting slabs are examined through, for example, the theory of bending viscous sheets. Finally, convection is studied holistically through a review of weakly nonlinear perturbation theories which predict three-dimensional patterns at convective onset, to matched-asymptotic boundary layer theories for strongly supercritical convection,

Progress in the study of mantle dynamics in the last 20 years has been driven by the rapid increase in computational power as well as ever growing sophistication in numerical models. Numerical methods are invariably the most versatile of all methods of study since they can examine strongly nonlinear convection without excessive simplifying assumptions, and can incorporate any relevant physics that can at least be articulated mathematically. Thus Chapter 4 reviews the numerical analysis of mantle dynamics by surveying the leading methods that are employed today. Classic methods of numerical modeling include finite-difference, finite-volume and spectral methods, all of which are outlined in Chapter 4; but perhaps the most powerful and versatile method is finite elements and this is given special attention. Some classic examples of how numerical analysis is used to attack key problems are also discussed; these include the omnipresent mantle complexities of thermochemical convection, phase changes and non-Newtonian rheology.

With the major tools of studying mantle convection surveyed in detail, the volume progresses to issues specific to the mantle itself. An obvious and key issue of mantle dynamics is the energy source for convection, which remains an active and at times controversial issue, and this is reviewed in Chapter 6. The energy budget of the Earth relies on various important quantities that are unfortunately not easily constrained. The loss of heat through the Earth's surface is a first-order observation but is problematic in that the measurements are difficult to make (e.g., measurements of conduction through the lithosphere are easily contaminated by the effects hydrothermal circulation) and global coverage of heatflow is difficult given the large variation in both crustal thickness and properties between and within oceans and continents. Secondly, the estimate of the heat sources inside the Earth is also difficult since it involves understanding the composition of the bulk Earth, which involves measurements of radioactive element concentrations from various sources such as continental crust, oceanic basalts and chondritic meteorites, but of course never directly from the mantle itself. Finally, basic understanding of convection from theoretical, numerical and analytical models (Chapter 3-5) allows construction of thermal histories of how the Earth cools and has evolved under the action of convection.

For Chapters 7-9 this volume concentrates on some of the key individual features of convective currents. Chapter 7 treats the problem of convection in the upper mantle its interaction with mid-ocean ridges and the oceanic lithosphere. It is widely recognized that the plates and lithosphere are the dominant convective thermal boundary layer of the mantle as it is cooled from above. How the oceanic lithosphere forms following complex magmatic processes at ridges can play a key role in the entire convective cycle, since, for example, melting at ridges can cause dehydration and strengthening of the lithosphere. How this same lithosphere transmits heat and thickens as it moves away from mid-ocean ridges is further a important feature of mantle convection. However, small-scale convection (as well as hotspot activity) in the sublithospheric asthenosphere can have a profound effect on how heat is transferred into the lithosphere. Moreover, plate motions can affect the structure of this small-scale convection, typically by aligning convective rolls with plate motion. Similar to small-scale convection is the convective instability of the lithosphere itself, which can lead to delamination and further change of lithospheric structure and cooling.

Chapter 8 continues with the plate and lithosphere as it enters subduction zones and becomes what is clearly the driving force for mantle convection, i.e., subducting slabs. The chapter first reviews the basic mechanism and energy release of slab descent. It then proceeds to examine evidence for slab structure from seismological observations, which can then be used to constrain dynamic models of sinking slabs as they descend through the subduction zone wedge environment and through mantle phase transformations. Phase changes have a particularly important effect on slabs because they can not only impede slab transfer into the lower mantle, but the slow kinetics inside cold slabs might cause metastable phases to exist, which potentially cause fine-scale buoyant stresses that could influence slab deformation and seismicity. One of the primary constraints on slab-related convection and mantle structure involves the geoid and topographic signature of subduction zones; in particular, the geoid over subduction zones is generally positive which suggests that the cold positive mass anomaly of the slab is supported by a viscosity increase with depth rather than by a downward deflection of the surface. Lastly, as discussed above, the volatile flux into the Earth is entirely coupled to subduction and slab dynamics, and this issue is necessarily discussed in detail.

To contrast the discussion of cold slabs, Chapter 9 concerns anomalously hot mantle, melting anomalies and the mantle's other primary convecting current, the elusive mantle plume. The chapter reviews first the observations relating to hotspots and melting, including discussion of age-progression volcanism (which has been the observational foundation of the stationary hotspot model); the topographic structure of hotspot swells (which suggest a larger mantle structure than just the volcanic edifice itself), the signature of large igneous provinces (thought to be associated with large starting plumes and/or the initiating of continental rifting), and the geochemical, petrological and seismological evidence for the depth of origin of hotspots. Next, the the process of hotspot melting and volcanism, the formation of plume swells, and the fluid dynamics of deep mantle plumes are examined and evaluated.

The final chapter in this volume, Chapter 10, involves the ongoing problem of interpreting observations of geochemical heterogeneity from the perspective of mantle convection theory. The chapter first reviews the observations and evidence for mantle heterogeneity, starting with its origin during early segregation of the mantle, crust and core, to its present state. As discussed above (Section 7.01.6.2), much of the evidence for current heterogeneity involves analysis of trace (incompatible) elements in mid-ocean ridge and ocean island basalts, as well as budgets of noble gases, and these primary constraints are explained and reviewed as well. Following the survey of observations, the chapter examines models of mixing, trace-element transport and layering in the mantle to address the fate, scale and isotopic signature of dispersed heterogeneities, as well as the stability of reservoirs of large-scale chemical heterogeneity. The problem of chemical evolution and heterogeneity remains one of the biggest unsolved problems in mantle dynamics and thus recent and future directions in this field are also discussed.

In the end, this volume of the Treatise on Geophysics is designed to give both a classical and state of the art introduction to the methods and science of mantle dynamics, as well as a survey of leading order problems (both solved and unsolved) and our present understanding of how the mantle works.

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