Geodynamic basis of heat transport in the Earth

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Dynamic processes of the Earth are based upon heat transport concepts derived from ordinary experience. But, ordinary experience can be misleading, especially when underlain by false assumptions. Geodynamic considerations traditionally have embraced three modes of heat transport: conduction, convection and radiation. Recently, I introduced a fourth, 'mantle decompression thermal tsunami' that, I submit, is responsible for emplacing heat at the base of the Earth's crust. Here I review, from the standpoint of geodynamics, energy, heat and thermal transport within the Earth that are connected in a logical, causally related way, and speculate that there might be a fifth mode: 'heat channelling', involving heat transport from the core to 'hotspots' such as those that power the Hawaiian Islands and Iceland.

Keywords: Earth, heat transport, geodynamics, heat channelling, core-mantle boundary.

DISCOVERING the true nature of continental displacement, its underlying mechanism, and its energy sources and modes of heat transport is among the most fundamental challenges of geoscience. The seeming continuity of geological structures and fossil life-forms on either side of the Atlantic Ocean and the apparent 'fit' of their opposing coastlines led Snider-Pellegrini[1] to propose in 1858, as shown in Figure 1, that the Americas were at one time connected to Europe and Africa and subsequently separated, opening the Atlantic Ocean. Half a century later, Wegener[2] promulgated a similar concept, with more detailed justification, that became known as 'continental drift'. According to Wegener's theory, in the past the continents were united, but about 300 million years (m.y.) ago broke apart with the pieces drifting through the ocean floor to their present locations.

Any theory of continental displacement requires a physically realistic mechanism and an adequate energy source. In 1931, Holmes elaborated upon Bull's[3] concept of mantle convection, originally suggested to explain mountain building, and proposed it as a mechanism for continental drift, publishing the illustration reproduced as Figure 2 (ref. 4). Three decades later the discovery of ocean-floor magnetic striations – symmetric to the mid-ocean ridge and progressively older with distance from it – was well explained[5] by 'seafloor spreading'[6], which became a crucial component of plate tectonics. The idea that the seafloor is extruded from the mid-ocean ridges, moves across the ocean basin and is 'subducted' into submarine trenches reinforced and seemed to justify the concept of mantle convection, as illustrated by the US Geological Survey diagram reproduced as Figure 3. To many, the explanation seemed so correct that mantle convection 'must' exist. But, as discussed here, there are serious, generally unrecognized problems with the concept of mantle convection and mantle convection has long been considered the dominant mechanism for heat transport within the Earth. So, one might ask, is there a different global geodynamic theory that can provide the means for heat transport and can account in a logical and causally related manner for the plethora of observations usually attributed to plate tectonics, but without necessitating mantle convection? I say yes[7–9] and describe it here.

Seventy years ago, Elsasser[10] published his idea, still popular today, that the geomagnetic field is produced by convective motions in the Earth's fluid, electrically conducting core, interacting with Coriolis forces produced by planetary rotation, creating a dynamo mechanism, a magnetic amplifier. Although the geomagnetic field reverses polarity irregularly, it has been remarkably stable for long periods of time, including intervals as long as 40 m.y. without reversals. Elsasser's convection-driven dynamo mechanism seemed to explain so well the generation of the geomagnetic field that for decades geophysicists believed convection in the Earth's fluid core 'must' exist. But, as discussed here, there are serious, generally unrecognized problems with the concept of Earth-core convection. So, one might ask, without Earth-core convection can the geomagnetic field be generated by the convection-driven dynamo mechanism? I say yes[8,11,12] and describe it here.

Confusion in the scientific literature as to the nature of the Earth's energy sources, their locations and the modes of heat transport can be traced to two erroneous assumptions: (1) since 1940, that the Earth's chemical and mineral composition resembles an ordinary chondrite meteorite; and, (2) since 1963, that the Earth formed from dust, condensed from an atmosphere of solar composition at very

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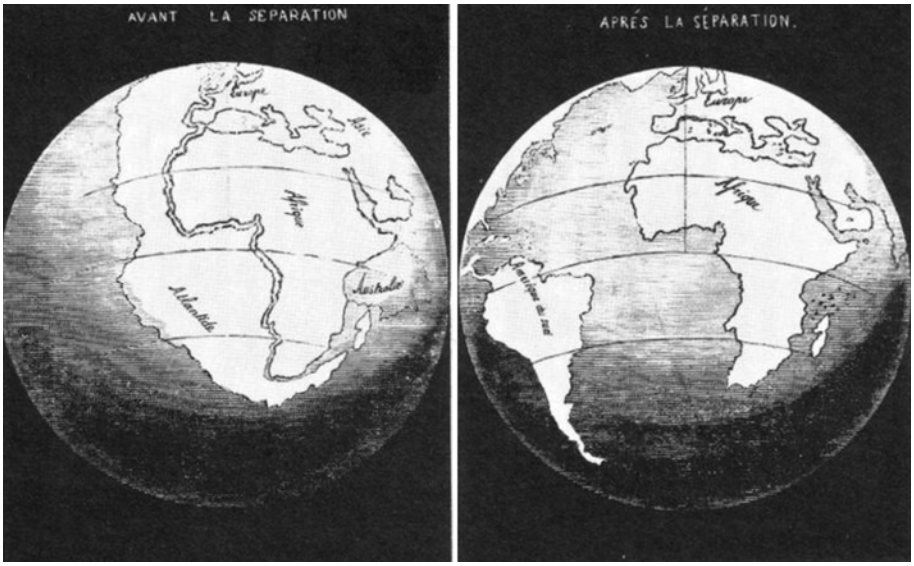

Figure 1. The opening of the Atlantic Ocean (reproduced from Snider-Pellegrini[1]).

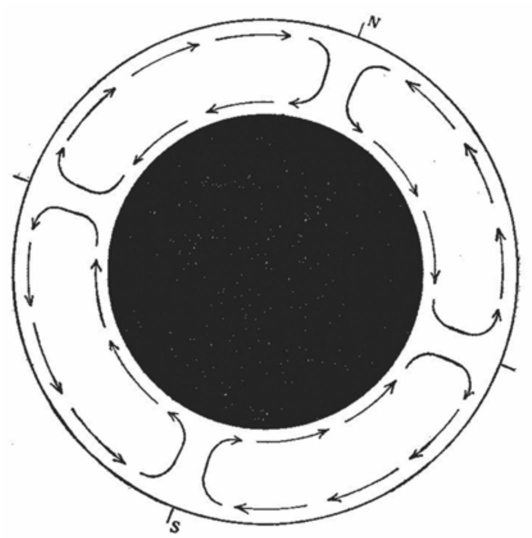

Figure 2. Schematic representation of mantle convection (from Holmes[4]). Reproduced with permission of the Geological Society of Glasgow.

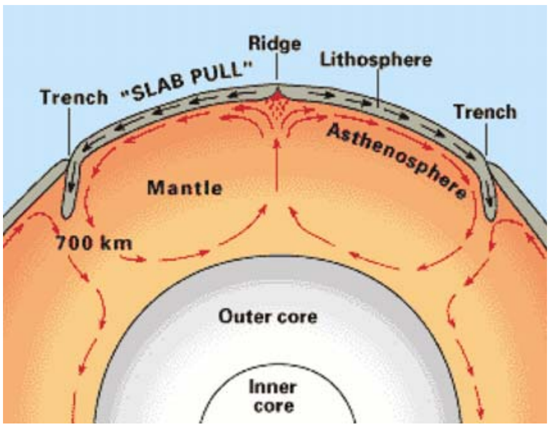

Figure 3. US Geological Survey schematic representation of mantle convection associated with plate tectonics theory.

low pressure, ca. 10^{-5} bar, that gathered into progressively larger grains, then rocks, then planetesimals, and finally planet Earth. Before reviewing the nature of Earth's energy, heat and heat transport, I describe why those two long-held assumptions are erroneous.

Enstatite chondritic Earth composition

The fundamental relationships connecting the isotope compositions of the elements of the Earth with those of the chondrite meteorites, and connecting the abundances of the non-gaseous chemical elements of chondrite meteorites with corresponding abundances of the elements in the outer portion of the Sun form the basis for the knowledge of the chemical and mineral composition of the Earth[13–15]. The similarity of corresponding non-volatile element ratios in the Sun and in chondrites attests to their common origin and to chondrites having had relative simple chemical histories. But not all chondrite are identical; they fall into three distinct groups: *carbonaceous*, *enstatite* and *ordinary chondrites*. These groups differ primarily in oxygen content, which causes their mineral compositions to be quite different[16–18], as illustrated in Table 1.

By the early 1930s, the internal structure of the Earth was thought to be simple, consisting of just the fluid core, surrounded by a uniform shell of solid rock called the mantle and topped by a thin crust[19]. Subsequent seismological evidence, though, indicated more complex structures for both the core and mantle. The first indication of Earth-core complexity came with Lehmann's 1936 discovery of the inner core[20]. Birch[21] and others assumed that the inner core was partially crystallized nickel–iron metal from the in-process freezing of the nickel–iron fluid core. That explanation had its origin in the belief that the Earth resembles an ordinary chondrite. In ordinary chondrites iron and nickel are invariably alloyed in the metal; all heavier elements are insufficiently abundant, even combined together, to produce a mass as great as that of the inner core. The rare, highly reduced enstatite chondrites were totally ignored.

By 1940, Bullen[22,23] had recognized a seismic discontinuity in the mantle, an interface where earthquake waves change speed and direction, at a depth of about 660 km, thus separating the mantle into two major parts, upper and lower. Additional seismic discontinuities were later discovered in the upper mantle. Bullen subsequently discovered a zone of seismic 'roughness' called D″ located between the core and the seismically featureless lower mantle[24–27]. Generally, seismic discontinuities within the Earth's mantle, including at D″, have been ascribed to physical changes in a medium of uniform composition, i.e. pressure-induced changes in crystal structure, rather than boundaries between layers of different chemical compositions[28]. This view of Earth developed because the Earth was thought to resemble an ordinary chondrite.

It is possible to show conclusively that if the Earth is like a chondritic meteorite as long believed for good reason, then the Earth is in the main like an enstatite chondrite, not like an ordinary chondrite. Imagine heating an iron metal-bearing chondrite. At some temperature below the melting point of the silicates, the iron forms a dense liquid alloy with the sulphides, analogous to the Earth's core surrounded by the solid silicate mantle. Figure 4 compares the iron alloy weight% of ordinary chondrites and enstatite chondrites with the weight% of the Earth's core. Clearly, only enstatite chondrites, not ordinary chondrites, have a sufficiently high iron alloy content to comprise a massive core planet like the Earth. Moreover, the mass ratios of petrologically determined parts of a primitive enstatite chondrite match quite precisely the seismically determined mass ratios of parts of the Earth that comprise the lower mantle and core (Table 2). This is strong evidence that the inner 82% of the Earth (lower mantle plus core) is like an enstatite chondrite and that its seismic discontinuities arise from boundaries between layers of different chemical composition.

Only nine elements comprise about 98% of the mass of an enstatite chondrite like Abee. The distribution of those elements between iron alloy and silicate is shown in Figure 5. Note that unlike in an ordinary chondrite, a portion of the high-oxygen-affinity elements (Ca, Mg, Si) occurs in the iron alloy part of the Abee enstatite chondrite as a consequence of its formation under highly reducing conditions. Generally, oxyphile elements are incompatible in an iron alloy and tend to precipitate when thermodynamically feasible. In the Earth's core, calcium and magnesium precipitated as sulphides at high temperatures, floated to the top of the core, and are responsible for the seismic 'roughness' at the core–mantle boundary. Silicon precipitated as nickel silicide forming the Earth's inner core (Figure 6). Uranium and thorium occur almost exclusively in the iron alloy portion of the Abee meteorite[29], as a consequence of formation under highly reducing conditions. Because the Earth resembles an enstatite chondrite (Table 2), I expect as much as 82% of our planet's uranium and thorium to reside in the Earth's core.

Table 1. Major element representation of the characteristic mineral assemblages of chondrite meteorites. The elements nickel and hydrogen are shown in instances necessary for clarity

Hydrous chondrites	
C1 carbonaceous chondrites e.g. Orgueil	Complex hydrous layer lattice silicate, e.g. $(Mg, Fe)_6Si_4O_{10}(O, OH)_8$ Epsomite, $MgSO_4 \cdot 7H_2O$ Magnetite, Fe_3O_4
Anhydrous chondrites	
C3 carbonaceous chondrites e.g. Allende	Olivine $(Fe, Mg)_2SiO_4$ Pyroxene $(Fe, Mg)SiO_3$ Pentlandite $(Fe, Ni)_9S_8$ Troilite, FeS
H, L, LL ordinary chondrites	Olivine, $(Fe, Mg)_2SiO_4$ Pyroxene $(Fe, Mg)SiO_3$ Troilite, FeS Metal (Fe–Ni alloy)
E3,4 enstatite chondrites e.g. Abee	Pyroxene, $MgSiO_3$ Complex mixed sulphides e.g. CaS (Mg, Fe)S Metal (Fe, Ni, Si alloy) Nickel silicide, Ni_2Si

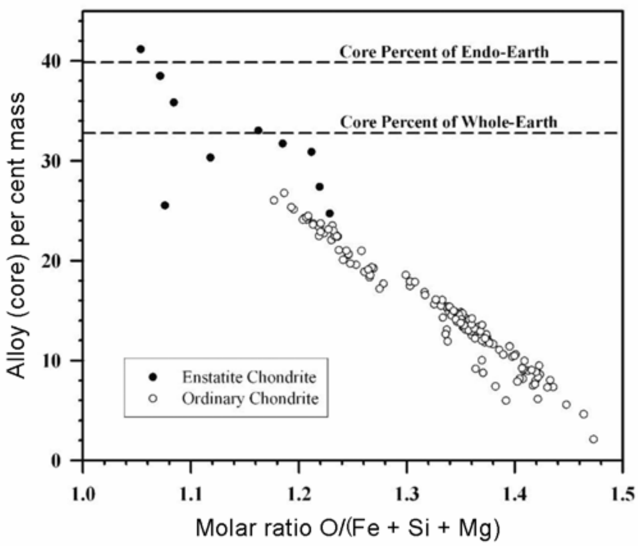

Figure 4. The per cent alloy (mainly iron metal plus iron sulphide) of 157 ordinary chondrites and nine enstatite chondrites plotted against a measure of oxygen content. The Earth as a whole, and especially the endo-Earth (lower mantle plus core) is like an enstatite chondrite and unlike an ordinary chondrite which has insufficient iron alloy. For additional information, see refs 8 and 51.

Table 2. Fundamental mass ratio comparison between the endo-Earth (lower mantle plus core) and the Abee enstatite chondrite. Above a depth of 660 km seismic data indicate layers suggestive of veneer, possibly formed by the late addition of more oxidized chondrite and cometary matter, whose compositions cannot be specified at this time

Fundamental Earth ratio	Earth ratio	Abee ratio
Lower mantle mass to total core mass	1.49	1.43
Inner core mass to total core mass	0.052	Theoretical 0.052, if Ni_3Si 0.057, if Ni_2Si
Inner core mass to lower mantle + total core mass	0.021	0.021
D″ mass to total core mass	0.09*	0.11**
ULVZ*** of D″ CaS mass to total core mass	0.012****	0.012**

*Calculated assuming average thickness of 200 km. **Average of Abee, Indarch, and Adhi-Kot enstatite chondrites. D″ is the 'seismically rough' region between the fluid core and lower mantle. ***ULVZ is the 'Ultra Low Velocity Zone' of D″. ****Calculated assuming average thickness of 28 km. Data from (refs 80, 86 and 87).

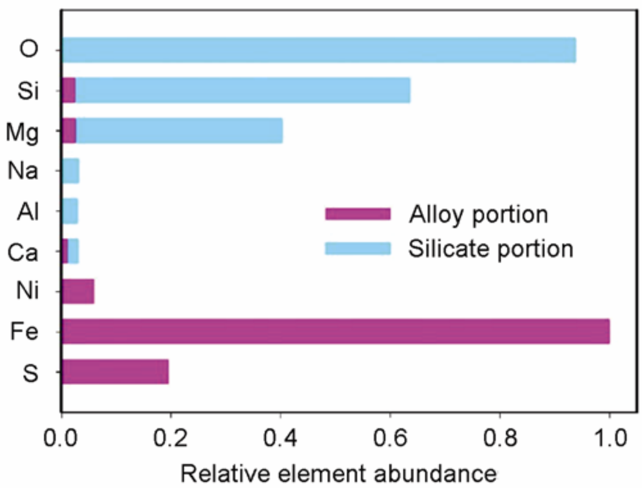

Figure 5. Distribution of major and minor elements between alloy and silicate portions of the Abee enstatite chondrite[85]. Note the occurrence of high-oxygen-affinity elements in the iron alloy portion that would not occur in an ordinary chondrite.

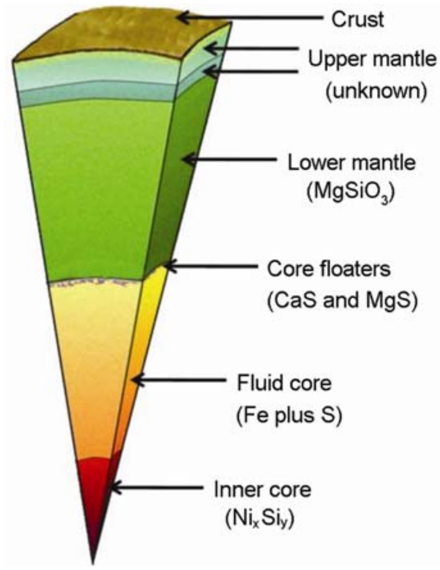

Figure 6. Chemical compositions of major parts of Earth, inferred from the Abee enstatite chondrite (see Table 2). The upper mantle, above the lower mantle, has seismically resolved layers whose chemical compositions are not yet known.

Formation of the Earth as a gas giant

Since the first hypothesis about the origin of the Sun and the planets was advanced in the latter half of the 18th century by Immanuel Kant and modified later by Pierre-Simon de Laplace, various ideas have been put forward. Generally, concepts of planetary formation fall into one of two categories that involve either (1) condensation at high pressures, hundreds to thousands of bar or (2) condensation at very low pressures.

Beginning with the 1963 seminal publication by Cameron[30], the scientific community concurred that the Earth formed from primordial matter that condensed at low pressure, ca. 10^{-5} bar. The 'planetesimal hypothesis' was accepted as the 'standard model of solar system formation'. But, as I pointed out from thermodynamic considerations, such low-pressure condensation would lead to terrestrial planets having insufficiently massive cores, as iron would form iron oxide and not remain as metal[8].

Thermodynamic considerations led Eucken[31] to conceive the Earth formation from within a giant gaseous protoplanet with molten iron (and the elements dissolved therein) raining out to form the core before the condensation of the silicate-rock mantle. By similar extended calculations, I have verified Eucken's results and deduced that oxygen-starved, highly reduced matter characteristic of enstatite chondrites and, by inference, also the Earth's interior condensed at high temperatures and high pressures from the primordial solar system gas under circumstances that isolated the condensate from further reaction with the gas at low temperatures[8,32].

The gaseous portion of primordial solar system matter, as is the Sun's photosphere today, was about 300 times as massive as all of its rock-plus-metal-forming elements. Complete condensation of the Earth formed a gas-giant planet virtually identical in mass to Jupiter[8,33]; its rocky core, that we now call Earth, was compressed by that great weight to about 64% of its present diameter. Early Earth as a Jupiter-like gas giant is no longer a strange idea, as such giant planets are observed in extrasolar systems closer to their star than Earth is to the Sun[34]. So, what became of Earth's giant gaseous shell?

A brief period of violent thermonuclear activity, the T-Tauri phase, occurs during the early stages of star formation with grand eruptions and super-intense 'solar-wind' that is sufficient to strip the gas envelopes from the inner four planets, as demonstrated by the Hubble Space Telescope image of an erupting binary T-Tauri star (Figure 7). The rocky Earth compressed by the weight of primordial gases remained, whose subsequent decompression is the basis and primary driving-energy source for many of the Earth's geological processes[7,9,35].

Earth's formation as a Jupiter-like gas giant leads to two powerful unanticipated deep-Earth energy sources: (1) protoplanetary energy of compression, stored from its gas-giant stage, the main driving energy for whole-Earth decompression dynamics[7–9] and the source for heat emplaced at the base of the crust[35]; and (2) georeactor nuclear fission energy that powers the geomagnetic field and provides the heat that is ultimately channelled to the surface as 'hotspots'[9,11,36,37].

Heat emplacement at the base of the crust

Since 1939, scientists have been measuring the heat flowing out of continental rock[38,39] and since 1952, heat flowing out of ocean floor basalt[40]. Continental rock contains much more of the long-lived radioactive nuclides than does ocean-floor basalt. So, when the first heat-flow measurements were reported on continental rock, the heat was naturally assumed to arise from radioactive decay. But later, ocean-floor heat-flow measurements, determined far from mid-oceanic ridges[41], showed more heat flowing out of the ocean-floor basalt than out of the continental rock measured away from heat-producing areas[42], 51 versus 33 mW/m^2 respectively. This seemingly paradoxical result, I suggest, arises from a previously unanticipated mode of heat transport that emplaces heat at the base of the crust, which I call mantle decompression thermal tsunami[35].

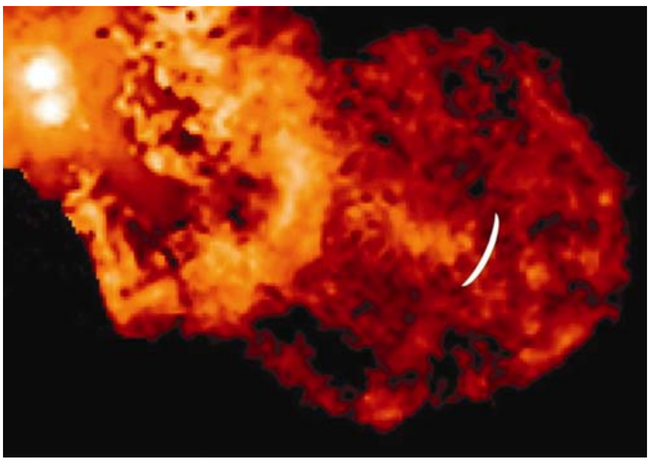

Figure 7. Hubble Space Telescope image of an outburst from the binary XZ-Tauri made in 2000. The white crescent shows the position of the leading edge of that plume in 1995, indicating a leading-edge advance of 130 AU in five years.

As the Earth decompresses, heat must be supplied to replace the lost heat of protoplanetary compression. Otherwise, decompression would lower the temperature, which would impede the decompression process. Heat generated deep within the Earth may enhance mantle decompression by replacing the lost heat of protoplanetary compression. The resulting decompression, beginning within the mantle, will tend to propagate throughout the mantle, like a tsunami, until it reaches the impediment posed by the base of the crust. There, crustal rigidity opposes continued decompression, pressure builds and compresses matter at the mantle–crust interface, resulting in compression heating. Ultimately, pressure is released at the surface through volcanism and through secondary decompression crack formation and/or enlargement. Mantle decompression thermal tsunami poses a new explanation for heat emplacement at the base of the crust, which may be involved in earthquakes and volcanism, as these geodynamic processes appear concentrated along secondary decompression cracks, and maybe involved in the formation of abiotic hydrocarbons[9,43]. Note that heat emplacement by mantle decompression thermal tsunami is distinct from heat delivered by the so-called mantle plumes, discussed below, which appear to be involved in intra-plate volcanism, such as presently observed along the East African Rift System[9].

Georeactor nuclear fission energy

Heat from radioactive decay of ^{235}U, ^{238}U, ^{232}Th and ^{40}K has long been (wrongly) considered as the main energy source for geodynamics processes, geomagnetic field generation and for the Earth's heat loss. For more than half a century, geophysicists have made measurements of near-surface continental and oceanic heat flow with the aim of determining the Earth's heat loss. Pollack *et al.*[44] estimated a global heat loss of 44.2 terawatts (TW, 1 TW = 10^{12} W) based upon 24,774 observations at 20,201 sites. The problem is that radioactive-decay heat alone cannot satisfy just the global heat loss requirements. Estimates of present-day global radiogenic heat production, based upon chondritic abundances of ^{235}U, ^{238}U, ^{232}Th and ^{40}K, typically range from 19 to 31 TW. These represent upper limits through the tacit, unrealistic assumption of rapid heat transport irrespective of radionuclide locations[45]. Moreover, it has long been known that the geomagnetic field originates at or near the centre of the Earth[46], so there must be an energy source there.

Confusion as to the nature of the location and nature of radionuclide energy sources within the Earth stems from the mistaken belief, prevalent for the past 70 years, that the Earth is like an ordinary chondrite meteorite rather than, as I discovered 30 years ago, a highly reduced enstatite chondrite[47–51]. In ordinary chondrites, which formed under more oxidizing conditions than enstatite chondrites[52], all of the radionuclides are found in the silicate portion. It has been (wrongly) assumed therefore that these would occur exclusively in the Earth's mantle and crust. Reports, however, have suggested that at high pressures ^{40}K might occur in the Earth's core[53]. The absence of core-heat sources in an 'ordinary chondritic Earth' led to the ad hoc suggestion, without corroborating evidence, that the inner core is growing by freezing, releasing the heat from gravitational potential energy and from crystallization which hypothetically provides useful energy rather than just slowing the assumed rate of freezing[54] or that heat is left over from planetary formation 4½ billion years ago[45].

The identification of the endo-Earth (lower mantle plus core) with an enstatite chondrite[51] made it possible for me to deduce that the bulk of the Earth's uranium resides within the core, eventually accumulating at the planet's centre, and to demonstrate the feasibility of its functioning as a natural nuclear fission reactor[36,37,55–57]. Initially, I demonstrated its feasibility through application of Fermi's nuclear reactor theory[36]. Subsequently, those calculations were verified and extended through georeactor numerical simulations conducted at Oak Ridge National Laboratory[37,57]. The nuclear georeactor is an unanticipated deep-Earth energy source that, I submit, produces the Earth's magnetic field[11,12,36,37,55–57]. Energy production from the nuclear fission of uranium can be potentially greater than from its radioactive decay, but may consume uranium at a faster rate. It is an open question as to whether thorium, possibly also in the Earth's core, exists under circumstances that might permit it to be converted to fissionable ^{234}U and thereby produce more energy than by radioactive decay alone.

Evidence of georeactor existence

Antineutrinos produced by radioactive decay products can in principle be detected and used to determine global radioactivity[58]. Antineutrinos produced by nuclear fission products can in principle be detected and used to verify the existence of a nuclear fission reactor at the Earth's centre, as the antineutrino energy spectrum of fission products differs from that of radioactive decay products[59]. In a recent report, geoneutrino measurements from the Kamioka Liquid-Scintillator Antineutrino Detector in Japan were combined with similar measurements from the Borexino detector in Italy[60]. The results of that study, summarized in Table 3 in terms of estimated heat production, provide evidence for the existence of the georeactor as well as confirming the shortfall in global energy balance. The difference between estimated global heat loss and radiogenic heat production, I posit, represents a portion of the stored energy of protoplanetary compression that is emplaced as heat at the base of the crust through the process of mantle decompression thermal tsunami[35].

State-of-the-art numerical simulations made at Oak Ridge National Laboratory, not only verified my conjecture that the georeactor could indeed function over the lifetime of the Earth as a fast neutron breeder reactor, but demonstrated that the georeactor would produce helium in the same range of isotopic compositions as observed in oceanic basalts[37,57,61], provided that highly mobile ^{3}H (half-life of 12.3 years) escaped the georeactor reactor core region, ca. 6 km in radius, before beta decaying to ^{3}He (Figure 8). The agreement between calculated georeactor helium isotope ratios and those observed in oceanic basalts provides strong evidence for the existence of the georeactor. The previous presumptive helium origin was primordial ^{3}He, assumed trapped since the Earth's formation, then mixed with just right the amount of ^{4}He from radioactive decay to yield the observed helium ratios[62].

Heat from the Earth's core

Helium, trapped in volcanic lava, is observed is a variety of geological settings. The $^{3}He/^{4}He$ ratios measured in basalt extruded at the mid-ocean ridges are remarkably constant, averaging 8.6 times the same ratio measured in air. The $^{3}He/^{4}He$ ratios measured in lava from 18 hotspots around the globe, such as the Hawaiian Islands, are greater than ten times the value in air. As shown in Figure 8, the georeactor numerical simulation results not only demonstrate fission-product helium in the range of compositions observed in basalt, but indicate a progressive rise in $^{3}He/^{4}He$ ratios over time as uranium fuel is consumed by nuclear fission and radioactive decay. Thermal structures, sometimes called mantle plumes, beneath the Hawaiian Islands and Iceland, two high $^{3}He/^{4}He$ hotspots, as imaged by seismic tomography[63,64] extend to the interface of the core and lower mantle, further reinforcing their georeactor-heat origin. To generalize, the high $^{3}He/^{4}He$ ratios measured in hotspot lavas appear to be the signature of 'recent' georeactor-produced

Table 3. Geoneutrino determinations of radiogenic heat production[60] shown for comparison with the Earth's heat loss to space[44]. See original report for discussion and error estimates

Heat (TW)	Source
44.2	Global heat loss to space
20.0	Neutrino contribution from ^{238}U, ^{232}Th and georeactor fission
5.2	Georeactor KamLAND data
3.0	Georeactor Borexino data
4.0	^{40}K theoretical
20.2	Loss to space minus radiogenic

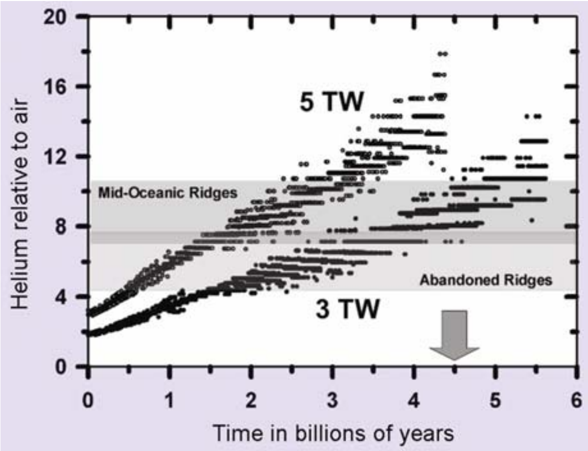

Figure 8. Fission product ratio of $^3He/^4He$, relative to that of air, R_A, from nuclear georeactor numerical calculations at 5 TW (upper) and 3 TW (lower) power levels[37]. The band comprising the 95% confidence level for measured values from mid-oceanic ridge basalts (MORB) is indicated by the solid lines. The age of the Earth is marked by the arrow. Note the distribution of calculated values at 4.5 Gyr, the approximate age of the Earth. The increasing values are the consequence of uranium fuel burn-up. Iceland deep-source 'plume' basalts present values[88] ranging as high as 37 R_A. Figure from Herndon[85].

heat and helium, where 'recent' may extend several hundred million years into the past.

The Hawaiian Islands and Iceland are two high $^3He/^4He$, ocean-floor-piercing, currently erupting hotspots with seismic imaging indicating that their heat sources arise from the core–mantle boundary. Mjelde and Faleide[65] recently discovered a periodicity and synchronicity through the Cenozoic in lava outpourings from these two hotspots that Mjelde *et al.*[66] suggest may arise from variable georeactor heat production, which may also begin to explain previously noted correlations between geologic surface phenomena and magnetic reversals[67].

As well as piercing the ocean crust, high $^3He/^4He$ hotspot volcanism presently occurs beneath continental masses: Yellowstone (USA) and Afar in the East African Rift System being two current examples. The massive flood basalts of the Deccan Traps of India (65 m.y. ago)[68] and the Siberian Traps (250 m.y. ago)[69] are likewise characterized by high $^3He/^4He$ ratios which, I submit, indicate georeactor-heat origin.

Tomographic images of the so-called mantle plumes beneath hotspots have become increasingly important for geological understanding. But, even with the advent of seismic tomography, there is still considerable controversy as to the true nature of mantle plumes and to the question of whether or not mantle plumes actually exist[70,71]. The mantle plume concept had its origins in Wilson's 1963 suggestion[72] that the volcanic arc comprised of the Hawaiian Islands formed as seafloor moved across a persistent, fixed hotspot. In 1971, Morgan[73] proposed that hotspots are manifestations of convection in the lower mantle. Here I describe the reasons that mantle convection is physically impossible and speculate on the idea of 'heat channelling' as a means of heat transport from the core–mantle boundary to the surface.

Mantle heat channelling

Since the 1930s, convection has been assumed to occur within the Earth's mantle[4] and, since the 1960s has been incorporated as an absolutely crucial component of seafloor spreading in plate tectonics theory. Instead of looking questioningly at the process of convection, many have assumed without corroborating evidence that mantle convection 'must' exist.

Chandrasekhar[74] described convection in the following way: 'The simplest example of thermally induced convection arises when a horizontal layer of fluid is heated from below and an adverse temperature gradient is maintained. The adjective "adverse" is used to qualify the prevailing temperature gradient, since, on account of thermal expansion, the fluid at the bottom becomes lighter than the fluid at the top; and this is a top-heavy arrangement which is potentially unstable. Under these circumstances the fluid will try to redistribute itself to redress this weakness in its arrangement. This is how thermal convection originates. It represents the efforts of the fluid to restore to itself some degree of stability.'

The lava lamp, invented by Smith[75], affords an easy-to-understand demonstration of convection at the Earth's surface. Heat warms a blob of wax at the bottom, making it less dense than the surrounding fluid, so the blob floats to the surface, where it loses heat, becomes denser than the surrounding fluid and sinks to the bottom. Convection is applicable in circumstances wherein density is constant except as altered by thermal expansion; in the lava lamp, for example, but not in the Earth's mantle. The Earth's mantle is 'bottom heavy', i.e. its density at the bottom is about 62% greater than its top (Figure 9). The potential decrease in density by thermal expansion, $< 1\%$, cannot make the mantle 'top heavy' as described by Chandrasekhar. Thus mantle convection cannot be expected to occur.

Mantle convection is often (wrongly) asserted to exist on the basis of a high calculated, dimensionless Rayleigh number[76]. In 1916, Rayleigh[76] applied the Boussinesq[77] approximation to Eulerian equations of motion to derive that dimensionless number to quantify the onset of instability in a thin, horizontal layer of fluid heated from beneath. The underlying assumptions, however, are inconsistent with the physical parameters of the Earth's mantle, viz. Earth's mantle being 'incompressible', density being 'constant' except as modified by thermal expansion, and pressure being 'unimportant' (quotes from Rayleigh[76]).

The same Boussinesq[77] approximation is often used in mantle convection models[78], despite the fact that the mantle is neither incompressible nor of constant density; the mantle is bottom heavy due to compression by the weight above. Sometimes convection models employ parameterization techniques that incorporate the Rayleigh number[79]. Details are rarely given that permit one to follow the physical process and to identify limitations and potentially inappropriate assumptions.

As an aid in understanding, it is instructive to apply the principle upon which submarines operate 'neutral buoyancy' to the Earth's mantle. The idea is that a heated 'parcel' of bottom mantle matter, under the physically unrealistic assumption of ideal, optimum conditions, will float upward to come to rest at its 'neutral buoyancy', the point at which its own density is the same as the prevailing mantle density.

Consider a 'parcel' of matter at the base of the Earth's lower mantle existing at the prevailing temperature, T_0, and having density, ρ_0. Now, suppose that the 'parcel' of bottom mantle matter is selectively heated to temperature ΔT degrees above T_0. The 'parcel' will expand to a new density, ρ_z, given by

$$\rho_z = \rho_0(1 - \alpha\Delta T),$$

where α is the volume coefficient of thermal expansion at the prevailing temperature and pressure.

Now consider the resulting dynamics of the newly expanded 'parcel'. Under the assumption of ideal, optimum conditions, the 'parcel' will suffer no heat loss and will encounter no resistance as it floats upward to come to rest at its 'neutral buoyancy', the point at which its own density is the same as the prevailing mantle density. The Earth radius of the 'neutral buoyancy' point thus determined can be obtained from the data upon which Figure 9 is based[80]; the 'maximum float distance' simply is the difference between that value and the Earth radius at the bottom of the lower mantle.

The relationship between 'maximum float distance' and ΔT thus calculated for the lower mantle is shown in Figure 10. At the highest ΔT shown, the 'maximum float distance' to the point of 'neutral buoyancy' is < 25 km, just a small portion of the 2230 km distance required for lower mantle convection, and nearly 2900 km required for whole-mantle convection. Even with the assumed 'ideal, optimum conditions' and an unrealistically great ΔT = 600 K, an error in the value of α by two orders of magnitude would still not cause the 'maximum float distance' to reach 2900 km. I use 'ideal' for purposes of illustration, but in nature 'ideal' does not exist, and only in certain quite limited instances is ideal behaviour even approached.

Decades of belief that mantle convection 'must' exist has resulted in a plethora of mantle convection models that, of course, purport to show that mantle convection is possible under certain assumed conditions. Generally, models begin with a preconceived result that is invariably achieved through result-selected assumptions. Although rarely, if ever, stated explicitly, in convection models, the mantle is tacitly assumed to behave as an ideal gas.

Stellar convection models involve a gravitationally compressed system of H_2 and He gas at ~ 5000 K that is thought to approach ideal gas behaviour, i.e. no viscosity, hence, no viscous loss. In such models a heated parcel of ideal gas expands and rises, never losing heat to its surroundings, and never coming to rest at 'neutral buoyancy'. The parcel maintains pressure equilibrium with its surroundings as it begins to rise, decompressing and expanding against progressively lower pressure, while maintaining its initial heat perturbation. The only impediment to such ideal-gas convection is if heat can be transported more rapidly by conduction and/or radiation than by convection.

Mantle convection models typically apply the same reasoning and assumptions as stellar convection models. A heated parcel of mantle matter is assumed to float ever upward decreasing in density, never reaching 'neutral buoyancy', while maintaining its heat content. But the mantle is not an ideal gas; it is a crystalline solid, not even a super-cooled liquid like glass. But, like its stellar counterpart, it assumed to behave 'adiabatically', i.e. to maintain the initial heat perturbation of the parcel, suffering no heat loss, although in reality the mantle: (1) is extremely viscous and thus subject to viscous losses; (2) potentially moves by convection slowly at a rate not too different from the rate heat is conducted; (3) has compositionally

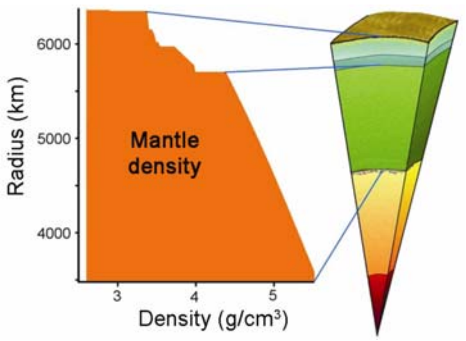

Figure 9. Density as a function of the radius in the Earth's mantle[80].

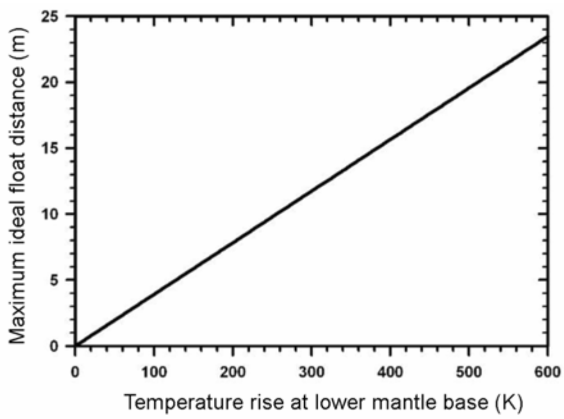

Figure 10. The 'maximum float distance' to 'neutral buoyancy' from the base of the lower mantle as a function of 'parcel' temperature rise. The value used for the coefficient of thermal expansion, $\alpha = 0.37 \times 10^{-5}$ K^{-1}, is from the standard reference state value of $MgSiO_3$ perovskite[89], reduced by 80% to take into account lower mantle base temperature and pressure, according to Birch[90].

different layers in the lower mantle; (4) may have crystalline phase boundaries in the upper mantle and (5) possesses unknown rheological properties. Earthquakes, for example, occur within the mantle to depths of about 660 km and signal the catastrophic release of pent-up stress. Processes and properties such as these, I submit, would readily block mantle convection. And, since whole-Earth decompression dynamics, mantle convection is not necessary to explain the observed seafloor topography even better than by plate tectonics[81]. The underlying principles of mantle convection, however, might operate on a micro-scale and contribute in a yet undetermined way to a process of mantle heat channelling.

Envision heat originating at a point on the Earth's core–mantle boundary. If thermal conduction alone were involved in its transport, one might expect the heat to be conducted to regions of lower temperature in a more-or-less hemispherical pattern. But seismic tomography appears to image vertical, column-like heat paths, for example, beneath the Hawaiian Islands, that cannot represent matter transport by convection for the reasons described above.

Water, uniformly distributed upon soil, often peculates downward by gravity in a nonuniform way, forming channels through paths of less resistance. An analogous process might occur in the Earth's mantle for the upward channelling of heat. Innumerable layers of buoyancy-driven micro-convection in conjunction with conduction, I speculate, operate to directionally bias and/or augment the flow of core-derived heat upward.

Geological consequences

It is helpful, from the standpoint of dynamics and heat transport, briefly to review geological processes stemming from the Earth's early origin as a Jupiter-like gas giant, as described by whole-Earth decompression dynamics. The weight of 300 Earth masses of primordial gases compressed the rocky portion to about 64% of the present Earth radius. The T-Tauri removal of the giant gaseous envelope left behind a vast reserve of energy, the stored energy of protoplanetary compression. That energy source is primarily responsible for decompressing the Earth to its present radius, but additional radiogenic energy (nuclear fission plus natural decay) may be required to replace the lost heat of compression; otherwise the Earth would cool and that would impede decompression.

A portion of the stored energy of protoplanetary compression is emplaced as heat at the base of the crust by mantle decompression thermal tsunami. That heat, I posit, is responsible for the geothermal gradient, the principal benefit of which is to provide a thermal barrier impervious to liquid water percolation; otherwise, Earth like Mars would lose its surface water. Heat emplaced at the base of the crust is responsible for much of the heat observed exiting through the Earth's crust and may be responsible for some of the Earth's volcanic activity, especially associated with plate boundaries.

A different source of heat, that produced by georeactor nuclear fission and radioactive decay within the Earth's core, is channelled to the Earth's surface in so-called plumes. This heat, recognized by associated high $^{3}He/^{4}He$ ratios, is responsible for hotspot volcanism, both island arc (e.g. Hawaiian Islands/Emperor Seamounts chain) and intra-continental (e.g. Afar, Yellowstone).

From Hadean Earth's beginning as a compressed sphere fully encased by continental rock, the dominant geological activity has been the formation of two kinds of surface cracks in response to decompression caused volume increases, hot cracks with underlying heat sources that extrude lava, and cold cracks that serve as the ultimate repositories for that lava. Together these produce the decompression necessitated increase in surface area and account for a plethora of observations usually attributed to plate tectonics, such as seafloor topography, but without mantle convection.

There are, however, some fundamental differences between whole-Earth decompression dynamics and plate tectonics: (1) Although competitive interactions between surface plates can occur, generally continents are not free to wander about the globe breaking up and reforming. (2) Decompression increases the Earth's radius, leading to changes in surface curvature that result in 'extra' continent surface area which, by buckling, breaking and falling over, produces fold-mountains[82], a mechanism that does not exclude additional mountain formation by plate collisions. (3) Changes in the Earth's radius may lead to potentially significant errors in magnetic paleolatitude determinations[83]. (4) Mantle convection does not occur.

Heat transport within the Earth's core

As is the case for the Earth's mantle, justification for Earth-core convection cannot be obtained by calculating the Rayleigh number because the Earth's core is neither incompressible nor of uniform density. Although the Earth's core is liquid, it is 'bottom heavy', i.e. its density at the bottom is about 23% greater than its top. The potential decrease in density by thermal expansion, < 1%, cannot make the core 'top heavy' as described by Chandrasekhar; thus convection is not to be expected. But, there is an even more serious impediment to Earth-core convection.

For sustained convection to occur, heat brought from the core bottom must be efficiently removed from the core top to maintain the 'adverse temperature gradient' described by Chandrasekhar, i.e. the bottom being hotter than the top. But, efficient heat removal is physically impossible because the Earth's core is wrapped in an insulating silicate blanket – the mantle, 2900 km thick that has significantly lower thermal conductivity, lower heat capacity, and greater viscosity than the Earth's core. Heat transport within the Earth's fluid core must therefore occur mainly by thermal conduction, not convection.

The geomagnetic implication is quite clear. Either the geomagnetic field is generated by a process other than the convection-driven dynamo mechanism, or there exists another fluid region within the deep interior of the Earth, which can sustain convection for extended periods of time. I have provided the reasonable basis to expect long-term stable convection in the georeactor subshell, and proposed that the geomagnetic field is generated therein by the convection-driven dynamo mechanism[11,12]. Heat produced by the georeactor's nuclear sub-core causes convection in the surrounding fluid radioactive waste sub-shell; heat is removed from the top of the sub-shell by a massive, thermally conducting heat sink (the inner core) that is surrounded by an even more massive, thermally conducting heat sink (the fluid core).

There are fundamental differences in convection-driven dynamo action in the georeactor sub-shell than in the Earth's core, as has long been wrongly believed. (1) The georeactor sub-shell contains a substantial quantity of continuously supplied, neutron-rich, radioactive fission products that beta decay, producing electrons which can generate magnetic seed-fields for amplification. (2) The dimensions, mass and inertia are orders of magnitude less than those of the Earth's core, meaning that changes in the geomagnetic field, including reversals and excursions, can take place on much shorter timescales than previously thought, in accord with observations[84]. (3) External effects may assume greater importance, for example, superintense bursts of solar wind might induce electrical currents and consequently Ohmic heating in the georeactor sub-shell, perhaps destabilizing convection and leading to magnetic reversals.

Scholarium

Science is very much a logical progression of understanding through time. Advances are frequently underpinned by ideas and understandings developed in the past, sometimes under circumstances which may no longer hold the same degree of validity[85]. All too often, scientists, being distinctly human creatures of habit, plod optimistically along through time, eagerly looking toward the future, but rarely looking with question at circumstances from the past which have set them upon their present courses. While scientific findings of the past cannot be ignored, one should look questioningly at past developments, and ask whether these are in conflict with the properties of matter as now known. Correcting past faltering leads to future progress.

1. Snider-Pellegrini, A., *La Création et ses mystères dévoilés* (*Creation and its Mysteries Unveiled*), Paris, 1858.
2. Wegener, A. L., Die Entstehung der Kontinente. *Geol. Rundsch.*, 1912, **3**, 276–292.
3. Bull, A. J., A hypothesis of mountain building. *Geol. Mag.*, 1921, **58**, 364–397.
4. Holmes, A., Radioactivity and earth movements. *Trans. Geol. Soc. Glasgow 1928–1929*, 1931, **18**, 559–606.
5. Vine, F. J. and Matthews, D. H., Magnetic anomalies over oceanic ridges. *Nature*, 1963, **199**, 947–949.
6. Hess, H. H., In *Petrologic Studies: A Volume in Honor of A. F. Buddington*, Geological Society of America, Boulder, 1962.
7. Herndon, J. M., Whole-earth decompression dynamics. *Curr. Sci.*, 2005, **89**(10), 1937–1941.
8. Herndon, J. M., Solar system processes underlying planetary formation, geodynamics, and the georeactor. *Earth, Moon, Planets*, 2006, **99**(1), 53–99.
9. Herndon, J. M., Impact of recent discoveries on petroleum and natural gas exploration: emphasis on India. *Curr. Sci*., 2010, **98**, 772–779.
10. Elsasser, W. M., On the origin of the earth's magnetic field. *Phys. Rev*., 1939, **55**, 489–498.
11. Herndon, J. M., Nuclear georeactor generation of the earth's geomagnetic field. *Curr. Sci.*, 2007, **93**(11), 1485–1487.
12. Herndon, J. M., Nature of planetary matter and magnetic field generation in the solar system. *Curr. Sci.*, 2009, **96**, 1033–1039.
13. Aller, L. H., *The Abundances of the Elements*, New York, Interscience Publishers, 1961.
14. Anders, E. and Grevesse, N., Abundances of the elements: meteoritic and solar. *Geochim. Cosmochim. Acta*, 1989, **53**, 197–214.
15. Suess, H. E. and Urey, H. C., Abundances of the elements. *Rev. Mod. Phys.*, 1956, **28**, 53–74.
16. Mason, B., The classification of chondritic meteorites. *Am. Mus. Novit.*, 1962, **2085**, 1–20.
17. Scott, E. R. D., Chondrites and the protoplanetary disk. *Annu. Rev. Earth Planet. Sci*., 2007, **35**, 577–620.
18. Story-Maskelyne, N. S., On the mineral constituents of meteorites. *Philos. Trans. R. Soc. London Ser.*, 1870, **160**, 198–214.
19. Jeffreys, H., *The Earth*, Cambridge University Press, Cambridge, 1929, 2nd edn.
20. Lehmann, I., *P. Publ. Int. Geod. Geophys. Union, Assoc. Seismol., Ser. A, Trav. Sci.*, 1936, **14**, 87–115.
21. Birch, F., The transformation of iron at high pressures, and the problem of the earth's magnetism. *Am. J. Sci*., 1940, **238**, 192–211.
22. Bullen, K. E., Note on the density and pressure inside the earth. *Trans. R. Soc. N. Z*, 1938, **67**, 122.
23. Bullen, K. E., The problem of the earth's density variation. *Bull. Seismol. Soc. Am*., 1940, **30**, 235–250.
24. Bullen, K. E., Compressibility–pressure hypothesis and the Earth's interior. *Mon. Not. R. Astron. Soc., Geophys. Suppl*., 1949, **5**, 355–398.
25. Manglik, A., New insights into core–mantle boundary region and implications for earth's internal processes. *Curr. Sci.*, 2010, **99**(12), 1733–1738.
26. Vidale, J. E. and Benz, H. M., Seismological mapping of the fine structure near the base of the earth's mantle. *Nature*, 1993, **361**, 529–532.
27. Bina, C. R., Mantle discontinuities. *Rev. Geophys*., *Suppl.*, 1991, 783–793.
28. Mao, W. L. *et al.*, Ferromagnesian postperovskite silicates in the D″ layer of the earth. *Proc. Natl. Acad. Sci. USA*, 2004, **101**(45), 15867–15869.
29. Murrell, M. T. and Burnett, D. S., Actinide microdistributions in the enstatite meteorites. *Geochim. Cosmochim. Acta*, 1982, **46**, 2453–2460.
30. Cameron, A. G. W., Formation of the solar nebula. *Icarus*, 1963, **1**, 339–342.
31. Eucken, A., Physikalisch-chemische Betrachtungen ueber die frueheste Entwicklungsgeschichte der Erde. *Nachr. Akad. Wiss. Goettingen, Math.-Kl*, 1944, 1–25.
32. Herndon, J. M. and Suess, H. C., Can enstatite meteorites form from a nebula of solar composition? *Geochim. Cosmochim. Acta*, 1976, **40**, 395–399.
33. Herndon, J. M., New indivisible geoscience paradigm 2011; arXiv.org/abs/1107.2149.
34. Seager, S. and Deming, D., Exoplanet atmospheres. *Annu. Rev. Astron. Astrophys*., 2010, **48**, 631–672.
35. Herndon, J. M., Energy for geodynamics: mantle decompression thermal tsunami. *Curr. Sci.*, 2006, **90**, 1605–1606.

36. Herndon, J. M., Feasibility of a nuclear fission reactor at the center of the earth as the energy source for the geomagnetic field. *J. Geomagn. Geoelectr.*, 1993, **45**, 423–437.
37. Herndon, J. M., Nuclear georeactor origin of oceanic basalt $^3He/^4He$, evidence, and implications. *Proc. Natl. Acad. Sci. USA*, 2003, **100**(6), 3047–3050.
38. Benfield, A. F., Terrestrial heat flow in Great Britain. *Proc. R. Soc. London, Ser. A*, 1939, **173**, 428–450.
39. Bullard, E. C., Heat flow in South Africa. *Proc. R. Soc. London, Ser. A*, 1939, **173**, 474–502.
40. Revelle, R. and Maxwell, A. E., Heat flow through the floor of the eastern North Pacific Ocean. *Nature*, 1952, **170**, 199–200.
41. Stein, C. and Stein, S., A model for the global variation in oceanic depth and heat flow with lithospheric age. *Nature*, 1992, **359**, 123–129.
42. Blackwell, D. D., The thermal structure of continental crust. In *The Structure and Physical Properties of the Earth's Crust, Geophysical Monograph 14* (ed. Heacock, J. G.), American Geophysical Union, Washington DC, 1971, pp. 169–184.
43. Herndon, J. M., Enhanced prognosis for abiotic natural gas and petroleum resources. *Curr. Sci.*, 2006, **91**(5), 596–598.
44. Pollack, H. N., Hurter, S. J. and Johnson, J. R., Heat flow from the earth's interior: analysis of the global dataset. *Rev. Geophys.*, 1993, **31**(3), 267–280.
45. Kellogg, L. H., Hager, B. H. and van der Hilst, R. D., Compositional stratification in the deep mantle. *Science*, 1999, **283**, 1881–1884.
46. Gauss, J. C. F., *Allgemeine Theorie des Erdmagnetismus: Resultate aus den Beobachtungen des magnetischen Vereins in Jahre 1838*, Leipzig, 1838, p. 73.
47. Herndon, J. M., The nickel silicide inner core of the earth. *Proc. R. Soc. London, Ser. A*, 1979, **368**, 495–500.
48. Herndon, J. M., The chemical composition of the interior shells of the earth. *Proc. R. Soc. London*, *Ser. A*, 1980, **372**, 149–154.
49. Herndon, J. M., The object at the centre of the earth. *Naturwissenschaften*, 1982, **69**, 34–37.
50. Herndon, J. M., Composition of the deep interior of the earth: divergent geophysical development with fundamentally different geophysical implications. *Phys. Earth Planet Inter*., 1998, **105**, 1–4.
51. Herndon, J. M., Scientific basis of knowledge on earth's composition. *Curr. Sci*., 2005, **88**(7), 1034–1037.
52. Herndon, J. M., Discovery of fundamental mass ratio relationships of whole–rock chondritic major elements: implications on ordinary chondrite formation and on planet Mercury's composition. *Curr. Sci*., 2007, **93**(3), 394–399.
53. Murthy, V. R., van Westernen, W. and Fei, Y., Experimental evidence that potassium is a substantial radioactive heat source in planetary cores. *Nature*, 2003, **423**, 163–165.
54. Loper, D. E., The gravitationally powered dynamo. *Geophys. J. R. Astron. Soc.*, 1979, **58**, 509–514.
55. Herndon, J. M., Planetary and protostellar nuclear fission: implications for planetary change, stellar ignition and dark matter. *Proc. R. Soc. London, Ser. A*, 1994, **455**, 453–461.
56. Herndon, J. M., Sub-structure of the inner core of the earth. *Proc. Natl. Acad. Sci. USA*, 1996, **93**, 646–648.
57. Hollenbach, D. F. and Herndon, J. M., Deep-earth reactor: nuclear fission, helium, and the geomagnetic field. *Proc. Natl. Acad. Sci. USA*, 2001, **98**(20), 11085–11090.
58. Raghavan, R. S. *et al*., Measuring the global radioactivity in the earth by multidetector antineutrino spectroscopy. *Phys. Rev. Lett*., 1998, **80**(3), 635–638.
59. Raghavan, R. S., Detecting a nuclear fission reactor at the center of the earth, 2002; arXiv:hepex/0208038.
60. Gando, A. *et al.*, Partial radiogenic heat model for earth revealed by geoneutrino measurements. *Nature Geosci*., 2011, **4**, 647–651.
61. Rao, K. R., Nuclear reactor at the core of the earth – a solution to the riddles of relative abundances of helium isotopes and geomagnetic field variability. *Curr. Sci.*, 2002, **82**(2), 126–127.
62. Craig, H. and Poreda, R. J., Cosmogenic ^3He in terrestrial rocks: the summit lavas of Maui. *Proc. Natl. Acad. Sci. USA*, 1986, **83**, 1970–1974.
63. Bijwaard, H. and Spakman, W., Tomographic evidence for a narrow whole mantle plume below Iceland. *Earth Planet. Sci. Lett.*, 1999, **166**, 121–126.
64. Nataf, H.-C., Seismic imaging of mantle plumes. *Annu. Rev. Earth Planet. Sci*., 2000, **28**, 391–417.
65. Mjelde, R. and Faleide, J. I., Variation of Icelandic and Hawaiian magmatism: evidence for co-pulsation of mantle plumes? *Mar. Geophys. Res*., 2009, **30**, 61–72.
66. Mjelde, R., Wessel, P. and Müller, D., Global pulsations of intraplate magmatism through the Cenozoic. *Lithosphere*, 2010, **2**(5), 361–376.
67. Larson, R. L., Geological consequences of superplumes. *Geology*, 1991, **19**, 963–966.
68. Basu, A. R. *et al*., Early and late alkali igneous pulses and a high-^3He plume origin for the Deccan flood basalts. *Science*, 1993, **261**, 902–906.
69. Basu, A. R. *et al*., High-^3He plume origin and temporal–spatial evolution of the Siberian flood basalts. *Science*, 1995, **269**, 882–825.
70. Foulger, G. R. *et al.*, The great plume debate. *Eos, Trans. Am. Geophys. Union*, 2006, **87**(7), 76; 80.
71. Sankaran, A. V., The row over earth's mantle plume concept. *Curr. Sci*., 2004, **87**(9), 1170–1172.
72. Wilson, J. T., A possible origin of the Hawaiian Islands. *Can. J. Phys*., 1963, **41**, 863–870.
73. Morgan, W. J., Convection plumes in the lower mantle. *Nature*, 1971, **230**, 42–43.
74. Chandrasekhar, S., Thermal convection. *Proc. Am. Acad. Arts Sci*., 1957, **86**(4), 323–339.
75. Smith, D. G., Display Devices, U.S. Patent 3,387,396, 1968.
76. Rayleigh, On convection currents in a horizontal layer of fluid where the higher temperature is on the under side. *Philos. Mag.*, 1916, **32**, 529–546.
77. Boussinesq, J., *Theorie Analytique de la Chaleur*, Gauthier-Villars, Paris, 1903.
78. Tackley, P. J., Self-consistent generation of tectonic plates in time-dependent, three-dimensional mantle convection simulations. 1. pseudo plastic yielding. *Geochem. Geophys. Geosyst*., 2000, 1:2000GC000036.
79. Davies, G. F., Heat and mass transport in the early earth. In *Origin of the Earth* (eds Newsom, H. E. and Jones, J. H.), Oxford University Press, New York, 1990, pp. 175–194.
80. Dziewonski, A. M. and Anderson, D. A., Preliminary reference earth model. *Phys. Earth Planet. Inter*., 1981, **25**, 297–356.
81. Herndon, J. M., Inseparability of science history and discovery. *Hist. Geo-Space Sci*., 2010, **1**, 25–41.
82. Herndon, J. M., Origin of mountains: The consequence of earth's early formation as a Jupiter-like gas giant. Submitted to *Curr. Sci*., 2011.
83. Herndon, J. M., Potentially significant source of error in magnetic paleolatitude determinations. *Curr. Sci*., 2011, **101**(3), 277–278.
84. Coe, R. S. and Prevot, M., Evidence suggesting extremely rapid field variation during a geomagnetic reversal. *Earth Planet. Sci. Lett*., 1989, **92**, 192–198.
85. Herndon, J. M., *Maverick's Earth and Universe*, Vancouver, Trafford Publishing, 2008, ISBN 978-1-4251-4132-5.
86. Keil, K., Mineralogical and chemical relationships among enstatite chondrites. *J. Geophys. Res*., 1968, **73**(22), 6945–6976.
87. Kennet, B. L. N., Engdahl, E. R. and Buland, R., Constraints on seismic velocities in the earth from travel times. *Geophys. J. Int.*, 1995, **122**, 108–124.
88. Hilton, D. R. *et al.*, Extreme He-3/He-4 ratios in northwest Iceland: constraining the common component in mantle plumes. *Earth Planet. Sci. Lett.*, 1999, **173**(1–2), 53–60.
89. Oganov, A. R., Brodholt, J. P. and Price, G. D., *Ab initio* elasticity and thermal equation of state of $MgSiO_3$ perovskite. *Earth Planet. Sci. Lett.*, 2001, **184**, 555–560.
90. Birch, F., Elasticity and constitution of the earth's interior. *J. Geophys. Res*., 1952, **57**(2), 227–286.

Received 16 December 2010; revised accepted 18 October 2011