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The persistent mantle plume myth

D. L. ANDERSON [a]

[a] Seismological Laboratory , California Institute of Technology , Pasadena , CA , 91125 , USA

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The persistent mantle plume myth

D. L. ANDERSON*

Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

Seismology, thermodynamics and classical physics—the physics associated with the names of Fourier, Debye, Born, Grüneisen, Kelvin, Rayleigh, Rutherford, Ramberg and Birch—show that ambient shallow mantle under large long-lived plates is hundreds of degrees hotter than in the passive upwellings that fuel the global spreading ridge system, that potential temperatures in mantle below about 200 km generally decrease with depth and that deep mantle low shear wave-speed features are broad, sluggish and dome-like rather than narrow and mantle-plume-like. The surface boundary layer of the mantle is more voluminous and potentially hotter than regions usually considered as sources for intraplate volcanoes. This means that the 'mantle plume' explanation for Hawaii and large igneous provinces is unnecessary. In isolated systems, heated from within and cooled from above, upwellings are passive and large, which suggests that tomographic features, and upwellings, are responses to plate tectonics, spreading and subduction, at least until melting introduces a small intrinsic buoyancy at shallow depths. Melting anomalies, or 'hotspots,' are side-effects of plate tectonics and are fed primarily by shear-driven processes in the boundary layer (BL), not by deep buoyant upwellings. A dense basal melange (BAM) component further stabilises the lower boundary layer of the mantle. Mid-ocean ridges and associated broad passive depleted mantle (DM) upwellings probably originate in the transition region. Deeper mantle upwellings are broad domes that stay in the lower mantle.

KEYWORDS: mantle geochemistry, plumes, perisphere, LLAMA, boundary layers, classical physics, tomography.

> The law that entropy always increases holds the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.
>
> —Sir Arthur Stanley Eddington, *The Nature of the Physical World* (1929)

Prelude (motivated by and adapted, paraphrased and updated from a 1991 article in this journal entitled 'The persistent myth of crustal growth' by Richard Armstrong)

A myth is a tale invented to explain some natural phenomenon. It cannot be falsified by any observation or theory. The mantle plume idea originated as a testable, albeit speculative, scientific hypothesis. As modified to explain compositions and volumes of island and continental basalts, and subjective correlations with lower mantle features, and as paradoxes accumulated and were ignored, it became a myth (e.g. Armstrong 1991; Dickinson 2003) or a just-so story. In philosophy, a just-so story, or *ad hoc fallacy,* is an unverifiable unfalsifiable explanation of some natural process. 'Mantle plume,' as currently used, has acquired the status of dogma, but it is seldom appreciated that it is without a sound logical (see Appendix 1) or physical foundation (Appendix 2). Any logical basis was extinguished as it was amended and modified. Physics and logic are routinely violated in the underlying assumptions and arguments (Tozer 1973; Larsen & Yuen 1997; Anderson 2007a, 2012a, b; Anderson & Natland 2007). Crust and volatile recycling, shallow melting, lithospheric extension, volcanism and shear- and plate-driven upwellings are now accepted as unavoidable consequences of plate tectonics. Nevertheless the myth persists and has distorted thinking about the Earth for decades. In science this is an old story, likely to be repeated, as defenders of common wisdom, e.g. an established paradigm or belief system, are seldom treated with the same scepticism as challengers of the *status quo.*

The conclusion is inescapable that terrestrial planets underwent essentially immediate—mostly irreversible—differentiation into relatively constant volume core, enriched crust and fluid reservoirs, and refractory degassed residual mantle that the Earth, on average, is cooling down and is periodically assembling and destroying supercontinents, and growing or shrinking its crust. Planets are not homogenised by self-driven convection. Potential temperatures, on average, in an isolated planet, decrease with time and with depth below the convective sublayer.

The geochemical basis of the cold Earth and plume ideas can be traced to Harold Urey and his Chicago

*dla@gps.caltech.edu

colleagues and former students, and their students, who advocated a cold origin for the planets, and a terrestrial crust that grew slowly over time from a primordial undifferentiated undegassed interior. Urey viewed planetary accretion as a gentle drawn-out process, involving accumulation of small planetesimals; he predicted primordial undegassed interiors for planets and a primordial basalt-free surface for the Moon. Cold accretion models predicted that planets should be little affected by igneous processing and degassing. However, physical considerations show that the history, internal structure and dynamics of the Earth are inexorably linked to the enormous energy of Earth and core formation and the subsequent cooling (Birch 1952, 1965; Arkani-Hamed 1994; Carlson & Boyet 2008).

The viewpoint advocated here challenges what has become accepted wisdom over the past 15 years, and this paper is polemical because it highlights the logical fallacies used by acolytes and the implications of the neglect of physics. The mantle plume myth has been repeated, amended and defended with assertions, selective data, *ad hoc* rationalisations, misconceptions and misunderstandings, and with straw man and logically fallacious arguments. In contrast to the original Morgan (1971) proposal, justifications now boil down to statements of belief–dogma-supported by invalid (pick-and-choose) statistics and circular reasoning, rather than by testable deductions from observations, physics or fluid dynamics; this makes the idea immune to falsification.

This paper is also philosophical in the sense that logic, rhetoric, paradigms and falsifiability are elements of the philosophy of science if not of science itself (Anderson 2007d). A paradigm differs from a scientific hypothesis in that it represents a belief and cultural system that was originally, perhaps, based on an observation or idea; it cannot be overturned, or disproved, by other evidence or future observations. It includes the believers, defenders and funders, and defence mechanisms. It involves a protective wall of auxiliary hypotheses, conventions and like-thinking advocates. Philosophers of science have noted that paradigms are not part of 'the scientific method' and, once established, are immune to evidence or logic; they must be destroyed, replaced or abandoned by external considerations, the equivalent of Trojan horses entering a strongly defended walled city. Some paradigms collapse simply because they become sophisticated (complex, lacking natural simplicity, weighted down). Hypotheses come and go; they either morph into theories as they survive testing and questioning, or they disappear. The scientific case against plume explanations for volcanoes has been made repeatedly but the concept survives because of its elegant (compact, simple, pleasingly ingenious) heritage, and because it has become a paradigm, which by definition has many defenders. And because the fatal objection—the Trojan Horse—is from physics and thermodynamics, not from geochemistry, experimental fluid dynamics and petrology, the specialities of the strongest remaining advocates.

Early versions of the paradigm implied a cold undifferentiated undegassed origin for the Earth and a primordial undegassed adiabatic lower mantle that is heated strongly from below and homogenised by convection. These concepts have been replaced by a dense basal melange (BAM) consisting of crust, primitive matter and recycled slabs that rises to the surface as it traps core heat. Recycling has now been accepted but, in current versions of the plume paradigm, recycled fragments are mixed with undegassed lower mantle, or gases from the core, before they return to the surface. Some numerical versions enforce whole mantle convection, a constant temperature core or injections of external energy or fluid, none of which are allowed in natural systems. These assumptions are modern versions of Maxwell's demon hypothesis, which was an early attempt to circumvent the second law by forcing desired behaviour on natural systems.

Richard Armstrong asked a series of questions, which I update. How can proto-planets and Earth not become degassed and differentiated before, during and soon after accretion; how can Earth rapidly differentiate a crust, core and atmosphere, yet retain an undifferentiated, undegassed homogeneous mantle? In the presence of enormous gradients in pressure and viscosity, how can the mantle convect as a single homogeneous fluid or even as a two-layer fluid? How can the core–mantle boundary of an isolated planet remain at constant temperature to provide an undecaying heat source for mantle plumes? How can crustal debris cycle to the core and back, sometimes very quickly, and not affect or be sheared into the shallowest mantle? How can large thick insulating surface plates not trap heat from the underlying mantle, away from ridges, while high-conductivity piles at the core–mantle boundary do that for core heat? In the presence of secular cooling and subduction, how can the average mantle maintain an adiabatic thermal gradient? Why does the ability to calculate a potential temperature, the temperature that a fluid mass would have if it were compressed or expanded to some constant reference pressure, imply that the mantle is adiabatic, convecting, well stirred and homogeneous? Why do the *ubiquitous* components of oceanic basalts (called Common, or FOZO components) differ from 'ambient' mantle erupted at ridges and why are they assumed to represent the deepest reservoirs? These are persistent fundamental issues that advocates of whole mantle convection and lower mantle sources for volcanoes have avoided, some for more than 20 years.

The idea that volcanic islands are rooted at the core–mantle boundary, or at the tops or edges of lower mantle 'superplumes' (an oxymoron), is an extraordinary claim. It was established as geochemical dogma starting in the 1970s and 1980s. The idea survives, as conventional wisdom often does, by inter-disciplinary misunderstanding, circular reasoning, repetition, rationalisation, self-citation, auxiliary assumptions, editors and by the simplicity (elegance) of the original concept. It has been defended by models and cartoons that violate the laws of physics and by experiments designed to make plumes, not to test the hypothesis. It has survived, not because of successful predictions or by lack of paradoxes, but by its flexibility, and because adherents are reluctant to abandon cherished concepts they grew up with and have vigorously defended during their education and research careers. Alternative views and objections have been ignored, questioned, downplayed and ridiculed, or not understood, and the paradigm, now a myth, is established as dogma.

Claims that the plume hypothesis is as well established as plate tectonics implies ignorance of the problems, paradoxes and failed predictions of the idea and a lack of understanding of mantle heterogeneity, melting behaviour, lithospheric dynamics, physics of high pressure and the power and generality of plate tectonics.

In science, conventional wisdom has inertia and is difficult to overturn. The implications of plate tectonics, recycling, internal heating, insulation, scaling, self-compression, self-organisation and of Fourier–Kelvin physics, have yet to be appreciated by isotope geochemists, and by geologists and geophysicists who have followed their lead.

INTRODUCTION

The above Prelude is motivated and paraphrased from a long, sparsely illustrated, article by Richard Armstrong, published on these pages 20 years ago, regarding persistent geochemical myths and the roles of differentiation and recycling in mantle geochemistry and dynamics. The targets of Armstrong's diatribe eventually adopted his concepts of recycling but combined them with deep mantle melanges of crustal and primordial materials, two-layer, one-layer, marble cake, depleted and undegassed mantles, and narrow radially zoned plumes connecting or traversing them. In other words, crustal recycling was married to Urey's (1952) concept of primordial planets. Armstrong's polemics also apply to these speculative revisions of Morgan's plume hypothesis. However, the more fundamental problem with current chemical geodynamics is associated with the suspension of the laws of physics and thermodynamics that are required to apparently make it work. As we will see, the disregard of physics, thermodynamics and fluid dynamic constraints is a fundamental and fatal objection to geochemical dogma regarding mantle dynamics. This article is the physics counterpoint of Armstrong's geochemistry critique and extends his philosophical musings about how science progresses, or is held back.

The mantle plume hypothesis and related geochemical models have been plagued with contradictions, failed predictions and paradoxes—called enigmas, conundrums, surprises and 'worrying' aspects in the geochemical literature—and problems regarding the definition, number, properties and locations of 'hotspots,' and the sizes and trajectories of plumes. There is no single physical or chemical attribute, or collection of attributes, that picks out 'the plumes' from thousands of other volcanoes; mantle plumes cannot be defined and therefore cannot be falsified (Courtillot *et al.* 2003; Anderson 2005). There is not even any agreement about the existence, or location, of features under Hawaii, the poster child of the plume myth (see below). The original, now largely abandoned, definition of 'plumes' involved self-driven, strongly buoyant, narrow upwellings from fixed points at great depth, which drove plate tectonics, kept ridges open and provided much of mantle heat-flow. Plumes were presented initially as an alternate to traditional physics-based models of large-scale mantle convective upwellings. Large-scale convective features are required by physics and by geophysical observations. These are now, misleadingly, called superplumes and incorporated into the paradigm.

HISTORY OF PHYSICS IN THE PLUME DEBATE

Background

Tuzo Wilson (1963) suggested that aseismic ridges, such as the Hawaiian and Emperor chains and the Chagos-Laccadive ridge can be explained by plates moving above a stationary hotspot in the mantle that could be as shallow as 200 km, just below the 'jet stream' of the rapidly moving plates. According to Campbell & Davies (2006), Morgan (1971) thought that Wilson's concept of shallow mantle hotspots had no physical basis and suggested that hotpots are narrow plumes of hot mantle, which rise vertically from fixed points on the core–mantle boundary. The experiments used to support this conjecture had no physical basis or counterpart in the solid Earth.

The plume debate is now one of the longest standing scientific controversies in the Earth sciences, having lasted longer than the age of the Earth, crustal growth and fixity-*vs*-drift controversies. Lord Kelvin and Sir Harold Jeffries played important roles in early geological debates, which pitted physics against geology, and fixists against mobilists. Their ghosts hover over present discussions. In these cases the geologists won because the physics was incomplete. Ironically, the physics that extends the age of the Earth and permits plate tectonics, results in a thick, strong, buoyant and hot surface boundary layer, a cooling subadiabatic interior, temperature and depth dependent properties and crustal recycling. Taken together, these eliminate the need for, or even the possibility of, narrow hot upwelling plumes and deep mantle sources. The low temperature, strength and intrinsic buoyancy of parts of the surface boundary layer explain why ancient materials can be trapped, and isotope ratios frozen in and isolated, in spite of plate tectonic resurfacing and 'vigorous mantle convection.' A thick insulating boundary layer, having the potential to provide within-plate basalts and to store ancient materials, is ubiquitous in the shallow mantle and does not need to be imported from the abyssal boundary layer, sometimes called D″ or the BAM. The physics used by Lord Kelvin to estimate the cooling time of the Earth, and the seismic waves named after Lord Rayleigh, show that the outer boundary layer of the mantle is twice as thick and much hotter than adopted in the plume paradigm. Lord Rayleigh also discovered Argon. The amount of Argon in the atmosphere is evidence that most of the mantle, and likely all of the deep mantle, is degassed rather than primordial. This hints at the important roles of classical physics in mantle evolution and dynamics.

Current mantle plume speculations are not only physics-free but highly adjustable, contradictory concepts that continuously change. In the last decade, at least 10 different versions of the plume hypothesis have been published in *Science* and *Nature* alone for Hawaii, including different locations, tilts, depths and sizes of the 'plume conduit' (see Sobolev *et al.* 2011; Torsvik *et al.* 2010; Ballmer *et al.* 2011; Cao *et al.* 2011; Weis *et al.* 2011; Cottaar & Romanowicz 2012, and references therein). Many more models, all different, were proposed earlier (Anderson & Natland 2005). The data in each of these rule out the others, as do better constrained seismic models (e.g. Katzman *et al.* 1998; Maggi *et al.* 2006). Publication in *Science* and *Nature*, hereafter S&N, is important since most non-seismologists get their geophysical information from these magazines and many seismologists rely on S&N for geochemical arguments, usually helium ratios, that they believe are definitive.

The number of plumes has varied considerably over the years, even among plume advocates. One school holds that only three or four currently active volcanoes—there is no agreement about which ones—are connected to deep superheated fixed sources by narrow flexible tubes, which are swept around by the mantle wind (Courtillot *et al.* 2003); the other hotspots are more related to tectonics and shallow sources. Another school holds that more than 30 volcanic and kimberlite provinces are connected by rigid vertical tubes to plume generation zones at the edges of lower mantle features (Torsvik *et al.* 2010). Others argue that plumes rise from the centers, not the edges, of lower mantle superplumes. Morgan & Phipps Morgan (2007) argues that both plumes and ridges are sourced in a 'plume-fed asthenosphere.' None of these studies use, or are consistent with, surface wave and normal mode studies (e.g. Anderson *et al.* 1992), which tell a completely different story; midplate volcanoes are sourced in the 200 km thick boundary layer of the upper mantle.

In the 1980s, the injection of coloured glucose syrup (the equivalent of Maxwell's demon) provided the 'fluid dynamic basis' for the balloon-on-a-string and flexible pipe models. Assumptions at the time included: the upper thermal boundary layer of the mantle is thin (~100 km), the underlying mantle is subsolidus, homogeneous and adiabatic, there is no radioactive heating or secular cooling below 100 km, there are no pressure or temperature effects except on density and viscosity, and 'hotspots' are anchored to fixed points in a deep insulating layer that is strongly heated from below and which traps heat. The adopted thickness of the upper boundary layer (McKenzie & Bickle 1988) is appropriate for cooling of the Earth for about 70 million years, an age that Lord Kelvin considered as reasonable. Cooling of the deeper mantle, either by conduction or by subduction, is ruled out in models based on this widely used 1988 geotherm.

Mantle geochemical models rely on other unphysical, mostly unstated, assumptions and intuitive interpretations of colour tomograms. The assumptions include: the Earth accreted cold and retained a primordial undegassed interior, regions of low *relative* seismic velocity unambiguously imply high *absolute* temperatures and low densities, convection homogenises, thermal conductivity is constant with depth, and the potential temperature of deep mantle is greater than can occur in the upper mantle. Other assumptions: ancient materials found in the ocean basins are (1) recently delaminated continental fragments from the latest cycle of continental break-up, transported laterally, or (2) ancient surface material cycled to the core–mantle boundary and back, vertically. The ubiquitous presence of enriched and ancient materials in the shallow mantle is one of the paradoxes of mantle geochemistry.

Early disbelief by physicists (Smith 1973a–c)

'*I don't believe them either, Harold*' was how Professor Keith Runcorn comforted an incredulous Sir Harold Jeffreys at a 1973 meeting of the Royal Astronomical Society devoted to mantle plumes. He went on to argue that buoyant plumes could not be narrow and that they are not analogous to plumes of smoke or thunderheads. Professor J. A. Jacobs added '*We may be worrying about something that doesn't exist.*' Volcanoes, rifts and faults are localised by tectonic processes and brittle material properties, not by fluid jets. David Tozer (1973) suggested that plumes were an *ad hoc* speculative fluid-dynamic attempt to localise volcanic activity. According to him, the plume hypothesis was unnecessary, unphysical and untestable; 'hotspots' were unavoidable side effects of plate tectonics rather than a new implausible form of planetary convection. Such side effects include plate induced flow, membrane stresses, tensional cracks, magma fracture and inhomogeneities in an asthenosphere that is above the melting point of some components because of recycling. In the traditional and physically plausible explanations for the presence and locations of volcanoes and the generation and extraction of magma, flood basalt volcanism such as occurs at Hawaii and Yellowstone, and upon continental break-up, are related to stress, cracks and tapping of magma in the deep crust and shallow mantle. Supercontinents (Pangea) and superplates (Pacific) trap heat, making subplate mantle hotter than subridge mantle. The secular cooling proposed by Lord Kelvin, his 2nd law and internal cooling by subduction of cold plates, creates a thermal bump in the asthenosphere, making it a plausible source for Hawaiian basalts. Heat from lower mantle superplumes, or a plume-fed asthenosphere, are not required.

The question arises, is volcanology a branch of geology and tectonics, as it used to be, or is it a branch of fluid dynamics and isotope geochemistry, requiring a specialised, unorthodox and controversial form of convection? Plume-like flow has never been observed in any self-consistent numerical or laboratory experiment. Narrow hot fast upwellings do not occur in realistic or properly scaled simulation; the modeller, acting as a modern day Maxwell demon, always induces such flow (Cordery *et al.* 1997; Larsen & Yuen 1997; Campbell & Davies 2006; Ballmer *et al.* 2011). All attempts to simulate mantle plumes involve at some point, violations of the second law, and the use of external sources of energy or material.

The scepticism, with which British physicists, Keith Runcorn, Harold Jeffreys, Jack Jacobs, David Tozer and others (Smith 1973a–c) viewed the mantle plume hypothesis, exactly 40 years ago, was well founded. The balloon-on-a-string cartoons have been used to illustrate the idea since the 1970s and are still used (e.g. Humphreys & Schmandt 2011; Anderson 2012a, b; and references therein). They are all based on externally induced perturbations or on travel-time-tomography colour images, rather than on closed isolated systems and spontaneous natural instabilities, or on well-constrained seismic studies.

PHYSICS AND MANTLE DYNAMICS

Classical physics

Much of plate tectonics, such as kinematics, force balances and tessellation of a sphere, can be understood without worrying too much about classical physics or material properties (Anderson 2007a, Chapter 4). 'Plume theory,' however, utilises the deep mantle and one cannot go far without considering the effects of compression, internal heating, thermal history of the mantle and core, and the kind of thermodynamics that controls the efficiencies of engines. Approximations that appear reasonable under near-surface and laboratory conditions not only do not work for an Earth-size planet but can lead to perpetual motion machines.

Seismology (surface, reflected and scattered waves, anisotropy etc.), geophysics, high-pressure physics, thermodynamics, complexity theory, petrology and lattice dynamics are the essential elements in any geodynamic hypothesis regarding the operation and evolution of planetary interiors (e.g. Anderson 2007a). Laboratory fluid dynamics, isotropic teleseismic relative travel-time tomography, and geochemistry play, at most, supporting roles. They play the dominant role in the mantle plume paradigm. Rheology and fracture mechanics are important in the surface boundary layer. It was well known in the 1950s and 1960s that stress, pressure, self-organisation, self-compression and scaling effects were important in planetary physics, tectonics and volcanology. They cannot be ignored and they must be treated in self-consistent ways. They are particularly important in any theory that involves thermodynamics and the properties and motions of the deep interior.

Classical seismology is associated primarily with the names of Rayleigh, Love, Jeffreys, Bullen and Gutenberg. Well before the 1980s it had already established that the Earth was layered, that the upper ∼1000 km of mantle was neither homogenous nor adiabatic and that there were ∼200 km thick boundary layers, Regions B and D″, just below the surface and just above the core (Figure 1). Another boundary layer was inferred from seismology, the region between 410 and 900 km, Region C. Region B, particularly the lower part, B″, is anisotropic and heterogeneous, which are diagnostics of shear- and buoyancy-driven boundary layers and, possibly, of the presence of fluids. Region B″ is more accessible and much larger, in terms of volume, than D″, and has higher homologous and potential temperatures than the top of D″ (Bunge *et al.* 2001; Moore 2008). Surface wave tomography showed that the surface boundary layer, both regionally and globally, is much thicker than the 100 km that is adopted in reference geotherms and in the mantle plume paradigm (Anderson *et al.* 1992; Anderson 2011; and references therein). Many of the arguments that have been used to support a D″ source for midplate volcanoes apply even more so to Region B″.

Between 1930 and 1960, classical physics and thermodynamics, in the hands of Francis Birch, John Verhoogen, Walter Elsasser, Vladimir Zharkov, Vladimir Magnitskii, Hans Ramberg, Subrahmanyan Chandrasekhar and David Tozer, played a large role in understanding the thermal history, structure and dynamics of the mantle, and the scaling from laboratory to planetary conditions and geological time. They built on a foundation, now called 'modern' and 'condensed matter' physics, laid by the previous generation of physicists. It was recognised that the Earth started hot and became a strongly differentiated and stratified body, complete with crust and core. It was speculated that volatiles were added as a late veneer. Broad upwellings were shown to characterise planetary convection; shallow advective motions were strongly influenced by a lithosphere stress-guide and decoupling by the weak asthenosphere. Plate tectonics and stresses in a cooling planet replaced older shrinking and expanding Earth concepts, and Beloussov's salt-dome-like balloon-on-a-string-like mantle diapirs (see Anderson & Natland 2005 and references therein).

It is classical physics, thermodynamics and seismology that make mantle plumes both unnecessary and implausible. Unfortunately, none of the above references, concepts, names or key phrases will pop up in a search for 'mantle plumes.' They exist outside the plume paradigm. The plume hypothesis was put forth as an alternate to large-scale mantle convection and was considered to be independent of plate tectonics or as a driver of plate tectonics.

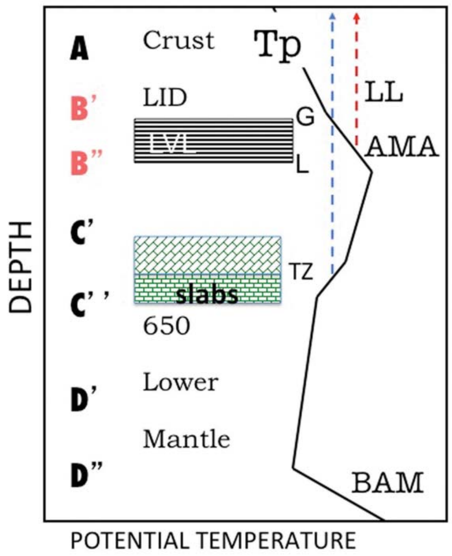

Figure 1 Nomenclature of the mantle and a schematic potential temperature (Tp) geotherm that illustrates the effects of lattice dynamics, slab cooling and radioactivity. Region B′ contains Laminated Lithologies (LL) and Region B″ contained Aligned Melt Accumulations (AMA). The lower mantle (Region D) starts below 900 km. The transition region of classical seismology is between 410 and ∼900 km. The Transition Zone (TZ) is the region between 410 and 650 km. The low-velocity anisotropic layer (LVL) extends from the Gutenberg discontinuity (G) to the Lehmann discontinuity (L). The adiabatic interior of canonical petrological geotherms is replaced by an internally heated-slab cooled region, which develops a subadiabatic gradient. The dashed lines are adiabats drawn from the TZ and surface boundary layers. (Figure modified from Anderson 2011).

Exit physics

'Plume intuition' is based on laboratory experiments and visual impressions of saturated false-colour tomograms, including artefacts, rather than on physics, thermodynamics and the natural behaviour of internally heated fluids at high pressure in an isolated planet. Evidence against the arguments, approximations, models and experiments used to support the plume idea, if not against the idea itself, are implicit in the textbooks, equations and dimensionless ratios of classical fluid and solid-state physics. The Prandtl and Rayleigh numbers, Gruneisen-like ratios, and the effects of pressure on thermal properties, all dictate against narrow hot plumes or fast jets from deep in planetary interiors (Appendix 2).

In the 1980s, physics and seismology played essentially no role in the hotspot debate or in construction of the still-used 1988 Cambridge reference geotherm (McKenzie & Bickle 1988). Existing compositional, thermal and dynamic models, based on equations of state, absolute seismic velocities, attenuation, anisotropy and wave-speed gradients, and thermodynamic constraints were replaced by visual impressions of false colour tomograms, interpreted in terms of temperature variations in a convectively homogenised adiabatic mantle.

During the 1980s and early 1990s, a number of papers appeared that simulated plumes by injection. The purpose was not to prove that plumes exist but to show how they would evolve if they existed. It is sometimes asserted, however, that such evidence supports, even requires, the existence of isolated narrow upwellings from deep in the mantle, certainly a *circular argument* (see Appendix 1). All such evidence is based on modelling that uses unphysical and unnatural boundary or initial conditions to initiate and maintain the narrow streams of buoyant fluid. In effect, a Maxwell's demon is used to localise and initiate a hot upwelling; Maxwell's and other thermodynamic relations and thermodynamic consistency preclude such behaviour. Nevertheless, simulations that violate thermodynamics and scaling relations, and that use external sources of heat and material rather than self-organisation, continue to be used to defend the plume hypothesis (e.g. DePaolo & Manga 2003; Campbell & Davies 2006). These fluid dynamic arguments are simply not relevant to the question of whether plumes can exist in an isolated internally heated Earth-size planet or are required to make volcanoes work (Anderson & Natland 2007; Anderson 2012a, b); they are *red herrings*. But ideas developed during the 1980s became frozen into the paradigm and are now considered self-evident orthodoxy. Unfortunately, they squeezed out the physics-based models of the 1960s and 1970s and introduced a large number of paradoxes, conundrums and variants because of their unphysical assumptions.

The most extreme examples used in support of the plume hypothesis actually suspend the laws of physics by turning off gravity and thermal conductivity while the required excess temperature and buoyancy builds up (Cordery *et al.* 1997; Ballmer *et al.* 2011). These methods are equivalent to holding down a hot air balloon while it is being filled and are distinct from normal Rayleigh-Taylor instabilities. Such highly artificial fluid dynamic simulations have been cited, usually by workers in other fields, as supporting the plume hypothesis (Ballmer *et al.* 2011; Humphreys & Schmandt 2011; Sobolev *et al.* 2011) but they cannot be used for that purpose (Larsen & Yuen 1997; Schuberth *et al.* 2009). The modellers themselves sometimes state that convection simulations are not intended to '*be realistic representations of the actual Earth*.' This qualifier is needed since such simulations do not, in fact, satisfy first order seismic constraints. This is also true of the 1988 Cambridge reference geotherm.

The strongest fluid dynamic evidence against the physical plausibility of natural plume-like instabilities in an isolated planet, and the easiest for a non-specialist (those unfamiliar with scaling relations and Birch's 1952 paper) to understand, is the fact that fluid dynamicists, acting as Maxwell's demon, continue to artificially insert plumes into the fluid, from the outside (Ballmer *et al.* 2011), since they do not occur otherwise (Schuberth *et al.* 2009). The sources of magma for volcanoes well away from ridges apparently are local and shallow (Anderson *et al.* 1992; Anderson 2011); the temperatures and volumes of magmas do not imply localised 'hotspots' nor do they require deep thermal upwellings (e.g. Bryan *et al.* 2010; Cañón-Tapia 2010). The number of paradoxes and exceptions in the canonical paradigm is additional evidence that some or all of the assumptions underlying the plume paradigm are wrong, or that the whole idea must be discarded.

FUNDAMENTALS

The second law of thermodynamics

In a closed isolated system, the second law of thermodynamics states that potential energy and order decrease with time. After the accretional stage, which adds mass and energy, a planet cools down by radiating energy to the universe, which has to be treated as part of the system. Except for this, and the small amounts of solar and tidal heating, the Earth is a closed system and plumes have to depend on energy in the Earth. Maxwell's demon was conjured up by James Clerk Maxwell in the 1860s in an attempt to circumvent the second law. The demon opens a trap door and allows only the faster ('hotter') molecules to flow through. However, the demon needs energy to observe the molecules and to process the information and this means that it cannot get around the second law. All calculations and simulations that create localised plumes by storing up and releasing, or inserting, buoyant masses of fluids, or that specify the location, shape and temperature of upwellings, violate the second law; the upwellings are not spontaneous and the modeller controls their temperatures, shapes and locations. Examples of each of the above are given in Campbell & Davies (2006) and the figures and references therein.

As a planet cools, conduction boundary layers thicken and subadiabatic gradients develop (potential temperatures decrease with depth, Figure 2, see Tackley *et al.* 1993; Bunge *et al.* 2001; Moore 2008). Violations of the second law occur in thermal history and geotherm

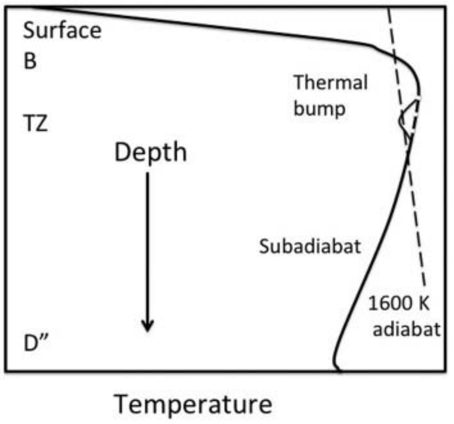

Figure 2 Spherically averaged geotherm, including the effects of cold slabs in the TZ. Ocean island basalts (OIBs) can be sourced at various levels in B (above 220 km depth) and colder MORB can be derived from TZ depths (>410 km). Seismologically inferred temperatures in the TZ (410 to 650 km) are on or below the 1600°K adiabat (dashed line), implying that adiabatic ascent from TZ depths may arrive at the surface with temperatures < 1600°K. Hawaii-like temperatures occur near 200 km depth (the thermal bump at the base of B) in the thermal BL (based on Tackley *et al.* 1993 and Anderson 2011; the broad bumps below TZ will be suppressed if most of the radioactivity in the mantle is in the crust and Region B).

calculations, and paradoxes arise, when one artificially imposes and maintains temperatures, temperature gradients or thicknesses of boundary layers (e.g. McKenzie & Bickle 1988). Such calculations do not satisfy global seismic constraints such as absolute seismic wave-speeds, wave-speed gradients, and the depths of temperature dependent discontinuities (Schuberth *et al.* 2009).

Thermodynamic consistency

The temperature dependence of viscosity and density has been used to justify the existence of narrow upwellings, or even to induce them, but this opens up the Pandora's Box of Thermodynamic Consistency. If volume, pressure and temperature change, so do thermal expansivity, thermal conductivity and specific heat, and they do so in predictable inter-related ways. One implication is that thermal conductivity decreases with depth in the surface boundary layer, which increases the inferred temperatures and the temperature gradients at shallow depths. A metasomatised (Pilet *et al.* 2008) or laminated boundary layer accentuates this effect. This means that high-temperatures exist deep in mature surface boundary layers. The deeper hotter parts of shear boundary layers lag behind the surface motions (Wilson 1963) and shear-driven magma segregation (Kohlstedt, & Holtzman 2009) can produce age-progressive volcanic chains (Conrad *et al.* 2010, 2011) in regions of lithospheric extension (Favela & Anderson 1999). Thus, the petrological options for midplate and alkali basalt sources—high temperature, metasomatised mantle, pre-existing melt—all exist in the boundary layer. The mechanisms available for bringing magma to midplate volcanoes from a shear-boundary layer include magma fracturing and shear-driven magma segregation. These sources and mechanisms are all related to plate tectonics and do not require 'excess temperature,' deep sources or ad hoc speculative forms of convection to localise volcanoes (e.g. Tozer 1973). The colder and more refractory parts of the boundary layer serve as permeability barriers to migrating melts and low diffusivity traps for ancient helium isotopes.

At sub-boundary layer depths, the effects of radioactivity, secular cooling and subduction create subadiabatic gradients, meaning that deeper upwellings, which must be passive, are colder than shallower ones (Figure 2). The effects of compression on thermal and transport properties shut down the possibility of small-scale instabilities and rapid jet-like upwellings in the deep mantle. The evidence for a subadiabatic geotherm is particularly strong for depths between 250 and 1000 km but subadiabaticity may occur, between boundary layers, throughout the mantle.

GEOCHEMISTRY AND MANTLE PLUMES

Mantle models based mainly on isotopes and assumptions (e.g. Kellogg & Wasserburg 1990), or on fluid dynamic simulations of plumes, enforced whole mantle convection, or on selected colour tomograms (Montelli *et al.* 2004), are quite different from those based on other considerations, such as physics and classical seismology (e.g. Birch 1952; Armstrong 1991; Anderson *et al.* 1992; Hofmeister 1999; Anderson 2007a; Moore 2008; Xu 2008).

Elements of Urey's cold accretion and primordial planet ideas, always implausible from any physics or energetics point of view, survive to the present and form the geochemical basis of the deep mantle plume myth. The belief that the lower mantle is undegassed underlies the assumption that high $^3He/^4He$ ratios imply high concentrations of ^3He, rather than low abundances of ^4He, Th and U. Geochemical models have been modified to include deep crustal recycling and the terms 'less degassed,' '^3He-rich' and 'more primitive' have replaced 'primordial' but the intent is the same. The geochemical components originally attributed to primitive mantle, and the core, are now known to be largely or entirely recycled surface materials, slab volatiles and ancient components trapped in the cold outer shell and in buoyant harzburgites and dunites.

Uranium and thorium play central roles in mantle dynamics and thermal history. Their products, Pb, He and heat, are associated with a number of geochemical paradoxes and conundrums, including the heat-flow, Pb- and He-paradoxes. The existence and persistence of these paradoxes suggest that the physical assumptions underlying geochemical models are wrong. Although Pb- and He-isotopes have been used to support the primordial mantle and plume myths, the effects of radioactive heating are ignored in the reference geotherm that has been used to define 'excess temperature' and as evidence of mantle plumes. The reader needs to be reminded at this point that, technically, thermal plumes *must* exist in any thermally convecting system. A 'plume' is any upwelling or downwelling that differs in density, and usually temperature, from its surroundings. In an isolated cooling planet, cold downwelling plumes are the dominant active form of convection; upwellings are passive, broad, slowly moving and are mainly responding to the downwellings. They are not 'mantle plumes' driven by their own thermal buoyancy. Morgan (1971), on the basis of atmospheric thunderheads, assumed the opposite; narrow upwelling plumes are compensated by slow sinking of the rest of the mantle.

RULES OF CONVECTION IN AN ISOLATED PLANET

Convection in an isolated internally heated planet that is cooling by conducting heat through a boundary layer to the surface, and radiating to space, is quite different from the behaviour of a pot of water on a stove that is powered by an external energy source. It is also different from numerical calculations that keep internal boundaries, such as the core–mantle boundary, at constant temperature, which also requires an external source of energy. These differences, plus the role of cold slabs in cooling the interior, result in geotherms that differ from those required to make the mantle plume idea viable.

Self-organisation

Does evidence from fluid dynamics, petrology and geochemistry require the existence of a separate physical process that generates narrow, long-lived upwellings of unusually hot rock; is the mantle plume model as well established as plate tectonics? The idea that mushroom-shaped plumes in the atmosphere, or in the lab, support, or can support, the idea may be intuitively appealing but is false on many levels. Even if true, it would not rule out other mechanisms for creating volcanoes, such as shear-driven magma in the boundary layer. Current versions of the mantle plume story are as inconsistent with thermodynamics and fluid dynamics as were the original ones; plate tectonic processes can readily account for all forms of volcanism. In other words, the existence, necessity and uniqueness of 'mantle plumes' are questionable at the most basic levels. The plume-inducing experiments of the 1980s and 1990s are far from being definitive proof of the existence of Morgan plumes in a natural situation. That was not their purpose; the purpose was to investigate the growth of artificially created narrow upwellings in a homogeneous fluid (see Appendix 2).

Mantle convection and plate tectonics are examples of self-organised far-from-equilibrium complex processes in which no single region or parameter can be studied in isolation or perturbed without affecting the whole. Thermal convection is a branch of thermodynamics, which requires that all parameters vary in an interconnected self-consistent way. Such systems cannot be understood by varying one parameter or perturbing one region; understanding requires exploration of a vast parameter space, involving the whole volume and many degrees of freedom. Thus, modern complexity theory, as well as classical physics, seismology and thermodynamics, rule out the canonical mantle plume idea and its multiple variants.

Early colour saturated tomographic images of the mantle were interpreted as evidence for whole-mantle convection, which was apparently in conflict with existing two-layer geochemical models and the concept of a primordial lower mantle. The whole-mantle convection idea was combined with the geochemical concepts of 'the convecting mantle'—a depleted well-mixed mid-ocean ridge basalt source—overlying a deep 'enriched source,' the basal mélange. Whole-mantle convection simulations, however, do not explain first order features of seismic models, including absolute wave-speeds, wave-speed gradients and the depths of major mantle discontinuities (e.g. Schuberth *et al.* 2009).

The eclogite engine

In 1966, the Australian petrologists Ted Ringwood and David Green proposed a generalisation of the sea-floor spreading hypothesis (Ringwood & Green 1966, figure 10) that is driven by cooling and the gabbro-eclogite transition. Because it involves chemical differentiation it is, in part, irreversible. In 1969, Anton Hales, on the basis of recently obtained seismic models proposed a top-down mechanism for driving the plates and lateral flow in the upper mantle. The modern version of these hypotheses includes plate-driven convection, shear-driven magma segregation (Kohlstedt & Holtzman 2009) and passive upwellings displaced by slabs to fuel mid-ocean ridges (Anderson 1989, 2007c, 2011, 2012a, b).

Thermal overshoot

'*If plumes are not the answer, what is?*' (Tackley 2006). A thermal overshoot, or bump, at the base of the surface boundary layer occurs in internally heated mantle convection models (e.g. Bunge *et al.* 2001; Moore 2008) and is the obvious source of midplate tholeiitic, picritic and komatiitic magmas. This overshoot plus the resulting subadiabatic gradient in the deeper mantle overturn the rationale for mantle plumes. Thermodynamics, top-down tectonics, plate-driven flow and the eclogite engine (Ringwood & Green 1966; Hales 1969; Anderson 2007c), provide the answers to the question that Tackley posed.

The conceptual problems associated with the original mantle plume and jet hypotheses, and the variants still used in geochemical and petrological discussions, have been recognised by Sleep (2007), Morgan (Morgan & Phipps Morgan 2007) and McKenzie (Priestley & McKenzie 2006), who are largely responsible for the hypotheses. The proposed modifications are similar to non-plume models since they involve passive heterogeneities (Anderson 2007b) and do not require mantle sources that are far below the boundary layer. J. Tuzo Wilson (1963) originally suggested that the source for the Hawaiian volcanic chain could be shallow. These recent modifications still ignore the effects of radioactivity, the thermal bump, subadiabaticity and the properties of the shear boundary layer, which eliminates both the need for deep sources and long distance lateral transport (horizontal plumes). The thermal bump, which is intrinsic to boundary layer and internally heated convection, removes the need to feed the shallow mantle with core–mantle boundary material, i.e. the plume-fed-asthenosphere and lateral-flow models. Shear-driven melt segregation and the buoyancy of harzburgite eliminate the need for deep hot upwellings to create oceanic swells and their volcanoes (Conrad *et al.* 2010, 2011; Zhou & Dick 2013), i.e. the mantle plume and jet models.

When the effects of internal heating, secular cooling, and compression and expansion on thermal properties are taken into account (Anderson 2011), the upper boundary layer of the mantle is >200°K hotter, and deeper boundary layers are >300°K cooler, than are assumed in canonical models of mantle convection and petrology (Figure 3). The importance of this result cannot be over-emphasised. It means that that hot mantle plumes are not only unnecessary but ruled out on thermodynamic grounds. However, a plausible alternative to mantle plumes becomes evident. Temperatures higher than inferred from mid-ocean ridge basalts (MORB) occur in the deeper parts of the midplate surface boundary layer, a layer that is missing at ridges. MORB appears to be the result of passive buoyant upwelling from deeper parts of the upper mantle. This type of model (Figure 1) is consistent with surface wave seismology, mantle anisotropy (Anderson *et al.* 1992; Ekstrom & Dziewonski 1998; Maggi *et al.* 2006) and mineral physics (Hofmeister 1999).

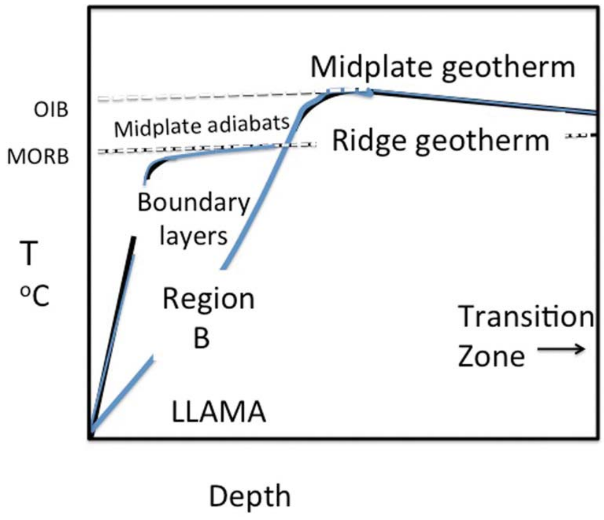

Figure 3 Schematic geotherms for the boundary layer (BL) and top of the upper mantle, showing a cold near-ridge passive upwelling from below the BL (labelled Ridge adiabat). The main features in the upper mantle are the 200 km thick midplate BL with a hot geotherm extending upwards from its base (the thermal bump) and the thinner ridge BL. The midplate geotherm includes the conduction layer, the thermal bump (the base of the BL), and the subadiabatic region below. The system is driven by plate motions and subduction. Theoretical temperature profiles between BLs are subadiabatic owing to internal heating and diverge by as much as 500°K from canonical geotherms. The seismically observed high-wavespeed gradients below 200 km require particularly strong subadiabats caused in part by slab cooling at depth (e.g. Xu 2008; Xu *et al.* 2008). The plate is the upper part of the BL.

THE ROLE OF BROAD-BAND WIDE-APERTURE SEISMIC IMAGING

The seismological basis of the plume hypothesis is a very crude form of imaging (teleseismic travel-time tomography, or TTT) that does not constrain the actual velocity structure but only lateral departures from an average background model, assuming isotropic, small and smooth perturbations that do not bend the nearly vertical seismic rays (Occam inversion). It cannot be used to discuss temperature, density or the presence of upwellings. A low shear-wavespeed region can be neutrally buoyant, a fine-grained shear zone, a dense eclogite sinker or a buoyant infertile peridotite fragment. A regional negative relative velocity anomaly may have higher absolute wave-speeds than the global average (e.g. VanDecar *et al.* 1995; Arrowsmith *et al.* 2005; Bastow 2012). This negates what has been considered the strongest seismological evidence for plumes.

Well-constrained seismic models use waveforms and reflected, scattered, converted and surface waves to constrain both vertical and horizontal structure, anisotropy, absolute seismic velocities and velocity gradients. In these studies deep plume-like and slab-like artefacts are suppressed and the great lateral extent of flat slabs and low-velocity zones are revealed; these are invisible in narrow aperture studies (e.g. TTT), since they are absorbed into the background structure. Significantly, seismic datasets show that wave-speeds in the mantle under and surrounding Hawaii are high in an absolute sense (Woodward & Masters 1991; Anderson 2011; and reference therein). In contrast, recent articles use, or refer to, studies that erroneously interpret low *relative* wave-speeds as evidence for low *absolute* wave-speeds and high *absolute* temperatures.

The easiest way for non-specialists to appreciate the non-uniqueness of models based on geochemistry and travel-time and body wave data is simply to compare models for Hawaii that have been published in the last 7 years in S&N, and the shifting positions taken in the 20 or so commentaries regarding plumes over the last decade (see references in Summary section and in Anderson (2011) and Cao *et al.* (2011)). Taken all together these papers and commentaries annihilate, rather than reinforce, each other. They are all inconsistent with more tightly constrained models of the mantle under Hawaii (e.g. Katzman *et al.* 1998; Maggi *et al.* 2006), expectations from high-resolution plume simulations (Ballmer *et al.* 2011) and wave front healing, which '*renders deep plumes seismically invisible*' (Hwang *et al.* 2011).

THE SHEARED BOUNDARY LAYER MODEL (LLAMA)

In the 1960s and 1970s, attention was focused on the surface boundary layer, the asthenosphere and tectonics, for the sources of magma and the driving mechanisms of plate tectonics. Theories to this effect were developed—by Orowan, Elsasser, Wilson, Chappel, Tullis, Bott, Hales, Ringwood, Uyeda and Forsyth—that were consistent with surface wave seismology as well as with more classical seismological and petrological constraints. Igneous petrologists focused on crust and shallow mantle sources. Important attributes of the boundary layer, which include the seismic lid and lithosphere (not the same) and the Gutenberg low-velocity layer (LVL) were the presence of melt and of anisotropy. The anisotropy was attributed to shear oriented olivine crystals or aligned magma sills. In the 1980s and 1990s, attention shifted to the other end of the mantle, largely as a result of the arguments in the previous section (*the MORB source is shallow, therefore…*) and of laboratory experiments in Australia (e.g. Anderson & Natland 2005; Anderson 2007d). The role of geochemists' influence on mantle dynamics was covered by Armstrong (1991). This is the period in which paradoxes started to appear. In this section, I return to the physical models of boundary layer processes.

Surface plates are driven by their own cooling and by dense slabs (Hales 1969; Elsasser 1971; Hager 1978). They are coupled to the interior via a 200 km thick thermal and shear boundary layer. The boundary layer collects the buoyant debris of mantle differentiation, which gets sheared into a laminated mega-melange. A laminated boundary layer acts as an insulating lid atop the so-called 'convecting mantle' (Anderson 2011; Heron & Lowman 2010) and is a plausible explanation for part of the temperature difference between ridges and midplate hotspots. The coupling of this layer to moving plates sets up a shear gradient that induces anisotropy, shear-driven magma segregation and upwelling (Figure 1). This thick buoyant boundary layer (seismic Region B) differs from the lithosphere and the plate but it includes them as well as the asthenosphere. It has been given various names such as perisphere and tectosphere to distinguish it from the lithosphere. Since it becomes Lithologically Laminated as a result of shearing, and contains shear-Aligned Melt Accumulations, it has been called LLAMA (Anderson 2011). It is the surface counterpart to BAM, the basal layer of the mantle (Region D″). Recycled crustal material and slab fluids are sheared into the buoyant surface layer, which is absent at ridges. Similar processes—insulation and trapping of upcoming heat—have been proposed in order to make D″ a plausible plume source but D″ has only one-forth the volume of LLAMA. Nevertheless, volcanic chains, and their longevity and volume, are often used, in the geochemical literature, as evidence for deep sources.

J. Tuzo Wilson (1963) suggested that many hotspots are related to ridges and that midplate volcanoes such as Hawaii may have shallow sources. The connection with ridges is even more dramatic when hotspot locations are compared with tomographic maps at depths of 100–200 km since most fall in ridge-related low-velocity features. Wilson pointed out that sources as shallow as 200 km deep can be regarded as relatively fixed and can generate parallel island chains. Deeper upwellings are blown around in the mantle wind. Narrow upwellings from deep sources, travelling through 'the convecting mantle' are unlikely to produce parallel island chains at the surface. On the other hand, regions of extension, which are related to the orientations of ridges and trenches, are self-perpetuating and are relatively fixed until boundary conditions change. On the Pacific plate, for example, the numerous fracture zones are parallel to each other and possibly to the mantle flow underneath. They are not controlled by deep fixed sources but they do influence the locations of volcanic chains. The trends of ridges, trenches and seismic anisotropy are probably better guides to mantle flow than are the trends of island chains, which reflect stress conditions rather than motion vectors.

Region B′ of the mantle (Figure 1) contains the cold strong thin lithosphere and the thicker seismic lid. Large-scale shear wave-speed variations in Region B″ are consistent with the presence of fluids and magmas, and variations in composition. The coherent anisotropy of this region is consistent with shear-aligned melt-rich sills (Kawakatsu *et al.* 2009) in an otherwise generally impermeable matrix. In the plate tectonic top-down hypothesis, 'the plate model,' developed by Hales, Elsasser and others, the associated long-wavelength density variations are the main driving force of plate tectonics via a stress-guide mechanism (also misleadingly called ridge-push). In the plume paradigm, plate tectonics is regarded as being driven from below, by narrow buoyant jets that break up continents, cause continental magmatism, keep ridges open and drive the plates. This is Morgan's 'strong plume' hypothesis, which is known from observations not to be tenable or necessary. Tomographic features attributed to plumes are fragmented and are apparently deflected by the 'mantle wind' and by slabs as if they were passive neutrally buoyant tracers in a heterogeneous mantle. Alternatively, such features may have nothing to do with plumes.

SUMMARY

Narrow, strong, active and rapid upwellings, driven by their own intrinsic thermal buoyancies, are implausible as a geodynamic engine from both fluid dynamic and classical physics points of view. Plumes from the deep mantle are unnecessary from a thermal point of view and, arguably, from a geochemical point of view. Relative to canonical geotherms and model assumptions used in geochemistry, lattice dynamic effects on phonon conductivity increase the temperature in the surface boundary layer by >200°K (Hofmeister 1999) and the sub-adiabatic thermal gradient in the interior decreases the temperature at the top of the lower boundary layer by >300°K (Bunge *et al.* 2001). Plumes are not evident in broadband, tightly constrained, seismic models or in high-resolution thermodynamically consistent fluid dynamic simulations. Experiments, calculations and theoretical geotherms that nominally support the plume hypothesis violate thermodynamic and fluid dynamic identities and scaling relations, and inferences derived from broadband seismology. The claimed correlation (Courtier *et al.* 2007) between magma temperatures and transition zone properties is not statistically significant.

Physics and seismology, plus complexity, self-organisation and planetary evolution theory, rule out the assumptions and geotherms that underlie the plume/jet explanations of 'hotspots.' In particular, the second law of thermodynamics is violated in all recent variants of the story and the studies used to support them. The thermodynamic and fluid dynamic issues with mantle plume speculations are basic and fatal. Thermodynamically consistent high-resolution mantle convection simulations support longstanding theoretical arguments and do not produce anything resembling the conceptual models of mantle plumes.

'It is thus with much kicking, dragging, and screaming that geoscientists are being brought to the realisation that all might not be well with the concept of mantle plumes' (McNutt 2007). The end game of the mantle plume paradigm is being played out on the pages of *Nature* magazine (VanDecar *et al.* 1995; Wolfe *et al.* 1997; Anderson & Natland 2007; Koppers 2011; Zhou & Dick 2013), where it began (Morgan 1971; Smith 1973a–c; Tozer 1973), and in letters and commentaries in *Science* magazine (e.g. Kerr 1999, 2001, 2003, 2006, 2009; Anderson 2001; Montelli *et al.* 2004; Wolfe *et al.* 2009; Cao *et al.* 2011; Harte 2011). Ironically, both early and later 'plume sightings' are likely due to similar TTT artefacts (Wright 1975; West *et al.* 2004; Anderson 2011; Bastow 2012), which are erased by use of more complete data sets (Anderson *et al.* 1992, 2011; Katzman *et al.* 1998; Ritsema *et al.* 2011).

Hofmann & Hart (2007) *'suspect that when the dust has settled over the mapping of plumes with seismic tomography, we will come to a consensus over the question of whether the Hawaiian hot spot, for example, is caused by a plume.'* Tackley (2006) asked *'If plumes are not the answer, what is?'* The dust has now settled and both questions have been answered (Doglioni *et al.* 2005; Kawakatsu *et al.* 2009; Hwang *et al.* 2011; Ritsema *et al.* 2011; Bastow 2012). The need, and seismic evidence, for deep mantle plumes has evaporated.

CONCLUSIONS

I finish as I began, with a paraphrase and update of Richard Armstrong's insightful and forceful critique, in this journal, of the interplay between tectonic and chemical speculations. There has been a constant borrowing of ideas and assertions between geochemistry and geodynamics, but little mutual understanding of underlying assumptions and pitfalls. Chemical geodynamic models are based on fluid injection experiments (Maxwell demons) and on visual inspection and intuitive interpretations of selected saturated colour images derived from crude forms of seismic imaging (TTT), which are regarded as evidence of through-going thermal features. Geodynamic modellers accept that isotope geochemistry constrains the depth, temperature, composition, helium content and degassing history of the sources of hotspot magmas. There is now an intimate intertwining of beliefs regarding mantle structure and convection. But physics has been left out of the discussion, and it rules out many of the bedrock assumptions. Plume- and paradox-free ideas and models developed in the 1960s and earlier by Holmes, Birch, Gutenberg, Verhoogen, Orowan, Elsasser, Hales, Ringwood and Green, in the 1970s by Armstrong, Jacoby, Forsyth, Uyeda, Garfunkel, Richter, Tatsumoto, Tozer and Kaula, and from surface wave and mantle anisotropy studies in the 1980s and 1990s, nicely account for contemporary and subsequent discoveries.

It has now been abundantly documented (see *Geological Society of America Special Papers* 388, 430 and 470 and www.mantleplumes.org) that: (1) essentially all predictions and assumptions of the plume paradigm are wrong; (2) that well-constrained seismological models, plate tectonics, recycling and surface boundary layer and transition zone sources and processes, can explain the geochemical, petrological and geophysical data and are, at the same time, compatible with physics and thermodynamics; and (3) that shallow subplate mantle is hotter than subridge mantle and that deeper mantle, on average, is subadiabatic. These can be all be verified without straying too far from the confines of S&N (Tozer 1973; Anderson *et al.* 1992; Tackley *et al.* 1993; Ekstrom & Dziewonski 1998; Hofmeister 1999; Anderson 2001; McNutt 2007; Pilet *et al.* 2008; Kawakatsu *et al.* 2009; Cao *et al.* 2011; Conrad *et al.* 2011; King 2011; Murakami *et al.* 2012). These papers do not support the assumptions underlying the plume hypothesis and few of them even mention plumes. Whether this, plus physics and second law violations, will drag '*kicking and screaming*' (McNutt 2007) geochemists, fluid dynamicists, and editors, to the realisation that the much amended plume myth needs retiring, remains to be seen. This is unlikely because of what philosophers of science call *incommensurability*; residents of paradigms are simply unable to communicate with or understand those with different perspectives and backgrounds. Mantle models based on the assumptions used by isotope geochemists, travel-time tomographers and laboratory fluid dynamics and those based on physics, thermodynamics and broad-band seismology represent different planets (Anderson 1999, 2007d).

ACKNOWLEDGEMENTS

The term pyrolite was coined 50 years ago by Ted Ringwood (Ringwood 1962). He argued for a chemically zoned upper mantle, with a harzburgite layer at the top of the mantle and eclogite segregations below. A few years layer he and his colleague David Green (Ringwood & Green 1966) developed the eclogite engine model of mantle dynamics and recycling to explain the zoned structure. Twenty years ago, on the pages of this journal, Richard Armstrong expressed his annoyance at most of the eminent isotope geochemists of the day for asserting that their data implied a homogeneous upper mantle model with no recycling and a primordial undegassed deep mantle that slowly degassed and shrank as it contributed to continuous crustal growth, and diverted its noble-gases to Hawaii, Iceland and Yellowstone. He argued that the lessons of plate tectonics had not sunk in. This effort is therefore dedicated to Ted Ringwood and Richard Armstrong. It is rare for scientists to point out to colleagues that they have built a house of cards; it is not the way to make friends and influence people. Without their examples, I would not have attempted this. Their models were built on the classic foundations of Bowen, Daly, Rubey, Hess and Birch, which provided a strong thermodynamic and petrological base that is missing in the plume myth. Einstein taught us that the right to search for truth, as a scientist, implies also a duty not to conceal what we have learned and not to ignore the lessons of Nature. History has taught us that Science and Nature are full of dead ends.

A paradigm that is past its shelf-life becomes a myth, and no amount of evidence, no number of paradoxes, can shake the faith of the true believers. Richard Armstrong

learned this from his personal experiences. For those of us in the mantle business, Francis Birch is a constant mentor. He introduced the concepts of self-compression and thermodynamic consistency into the solid Earth sciences. If more fluid dynamic modellers and isotope geochemists had studied his work, this small addition to it would not have been necessary. I learned petrology and the importance of self-consistency and the zoned upper mantle from Ted Ringwood. His upper mantle and eclogite engines models of 50 years ago (Ringwood 1962; Ringwood & Green 1966) are powerful alternatives to the plume hypothesis. I learned to respect wisdom and leadership from Anton Hales. I learned about low-velocity zones and the power of classical seismology from Gutenberg. Armstrong, Birch, Gutenberg, Ringwood, Tatsumoto and Gast provided the background in seismology, petrology, geochemistry and the logical framework that physically realistic models must be based on. Lessons learned as an undergraduate at RPI from Professor Robert E. Whallon's courses—Logic and Argument, Basic Problems in Philosophy of Life, History of Philosophy, Philosophy of Science—are evident in this contribution. Logic is as important as physics and isotopes. Logical fallacies are as fatal to a scientific hypothesis as are violations of the 2nd Law.

I appreciate critical reviews by Alan Smith, James Natland, Warren Hamilton and Michele Lustrino. I have followed their advice, but they bear no responsibility for this version.

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APPENDIX 1

THE 'LOGICAL' BASIS OF THE PLUME HYPOTHESIS

There is no physical basis for the plume hypothesis. When examined closely, there is also no logical basis. It has no predictive power. Any logical basis that it once had was extinguished as it was amended, modified and reformulated to account for each new observation. It is not possible to prove that a hypothesis is wrong; one can only show that it is improbable or is not as good as other hypotheses (using the Null Hypothesis or other statistical tests). Demonstrating that a hypothesis violates the 2^{nd} law is about as good as one can do when asking if a hypothesis is 'impossible.' However, one can also, using formal logic, sometimes demonstrate that conclusions do not follow from premises. Several examples are given in the following sections.

Assumptions

In the logical analysis of arguments one focuses on whether the conclusions follow from the premises; the premises are not challenged. Before we get to that point, however, it is useful to examine some assumptions and premises. The 1988 Cambridge geotherm—the reference for excess temperature and the presence of hot jets—is based on six critical, unphysical and unnecessary assumptions: 1) mantle cooling does not extend deeper than 100 km; 2) the temperature at this depth is $\sim$1300°C; 3) the mantle below this depth is adiabatic, homogeneous and composed of horizontal isotherms; 4) thermal conductivities and thermal gradients are constant with temperature and with depth; 5) the mantle contains no U, Th and K; and 6) the mantle is not cooling. It is these assumptions that made hot jets feasible, in fact, required. In addition to the obvious problems with these assumptions it is well known that cooling extends twice as deep as assumed, that the mantle is not homogeneous or adiabatic below 100 km, or even 200 km, and that normal ridge and ambient subplate mantle has lower seismic wave-speeds, below some 100 km depth, than occur under midplate volcanoes. The cumulative effect of these assumptions is an underestimate of ambient upper mantle potential temperatures by about 200°K. This, plus the thermal bump argument, eliminates the thermal arguments for hot jets and reverses their conclusions. This affects all subsequent arguments for excess temperatures under hotspots.

The most blatant assumption underlying the plume myth is that ambient upper mantle temperatures cannot exceed 1300°C. This assumption alone is largely responsible for the persistence of the plume myth. This thermal barrier has been considered to be an absolute constraint. The most innocuous assumptions, however, are those that are unquestioned or 'self-evident,' such as *'Temperatures increase with depth; material brought up from the deep mantle has to arrive at the surface with higher temperatures than exist in the shallow mantle… OIB sources are therefore in the deep mantle.* This sounds reasonable but ignores the effects that radioactivity, secular cooling and subduction have on the geotherm.

Paradigms and Paradoxes

Philosophers of science have noted that editors are the gatekeepers of conventional wisdom and they keep dying paradigms alive by their choices of papers, reviewers and commentators, by rejecting 'unorthodox' ideas and by publishing rebuttals to conflicting ideas that manage to slip past (e.g. DePaolo & Manga 2003; Hofmann & Hart 2007; Tackley 2006; Koppers 2011). Mass extinctions, British and Brazilian geology, continental deformation, kimberlites, continental break-up, recycling of the oldest terrestrial rocks, 'anomalous' noble-gas ratios, diamonds and oil have all been attributed, in general science magazines such as Science and Nature (Figure 4) to fossil,

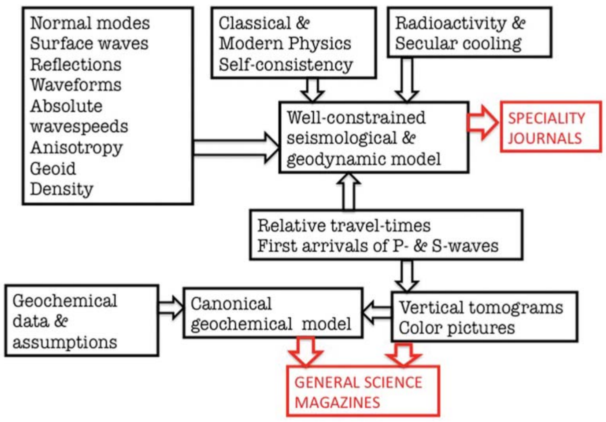

Figure 4 Well-constrained models of the mantle use a large arsenal of tools (upper portion of diagram) and tend to be published in geophysical and other specialty journals. Subsets of data lead to more speculative models that require a large number of assumptions and often contain artefacts that are a result of these assumptions and limitations of the data (lower portion of diagram). These models tend to be published in general audience weekly magazines accompanied by news releases and editorial comments about a new 'plume sighting.' Rebuttals and corrections to the 'new' theories, often highly technical, are published elsewhere.

decapitated or incubating plume heads or lateral plumes (as evidence that apparently supported the mantle plume concept evaporated) in letters and commentaries by editors and news writers (e.g. VanDecar *et al.* 1995; Wolfe *et al.* 1997, 2009; Arrowsmith *et al.* 2005; Kerr 2009; Editor 2011, http://www.nature.com/ngeo/journal/v4/n12/full/ngeo1348.html). Articles and letters in S&N have claimed that new seismic techniques made it possible to image multiple plumes in the mantle. The rebuttals to these speculations are almost always published elsewhere, and the original articles continue to be cited. The absence of any geophysical evidence for plumes, where they are expected or make geological sense, has been attributed to lack of resolution, up-side-down drainage from distant upwellings or to plumes that are no longer extant.

Paradox and paradigm are the Yin and Yang of science. Chandrasekhar remarked, '*When you really understand the physics, there are no paradoxes*.' This is where physics and logic meet. New paradigms are sometimes built on the paradoxes of the old and sometimes on completely different, more solid, foundations [this was not the motivation for the plume myth (Anderson 2007d)]. Paradoxes are often tolerated if there are no apparent alternatives, or if you become addicted to your paradigm (or do not understand, or know about, the physics that underlies the scepticism). In Plato's prisoners-in-a-cave parable, shadows of puppets are 'reality,' and physics is the 'outside world.' When paradigms become more faith-, or assumption-, based than evidence-based, they become myths and are abandoned by scientists, usually younger ones or ones trained in different traditions or disciplines, and eventually by editors of 'mainstream' publications. The existence of paradoxes can mean that physical laws are being violated or that underlying assumptions and logic are wrong. In most cases, changing, dropping or reversing assumptions can remove paradoxes. For example, the canonical geochemical model for OIB is based on the assumptions discussed previously and listed at the beginning of the next section. *Reductio ad absurdum* is a form of argument that seeks to demonstrate that a hypothesis or an assumption is true by showing that a false, untenable or absurd result follows from its denial or reversal. The following 'hypothesis' is the inverse of the canonical model:

> OIBs, including Hawaiian magmas, are from the thick surface boundary layer, which represents ambient subplate mantle; passive subridge upwellings from the transition zone are colder because of subadiabaticty; MORB helium ratios are low because of accumulated ^{4}He in this ancient relatively isolated reservoir. High ratios are due to the absence of U and Th.

Not only are the predictions of this 'hypothesis' not absurd, but they satisfy physical constraints and surface wave data (e.g. Anderson *et al.* 1992), and remove the canonical model paradoxes.

In rare cases, paradoxes occur, even in physics, because the physics is incomplete or not understood. This was the case in the age of the Earth and continental drift controversies; incomplete physics was responsible for the long neglect of self-organisation, complexity and surface forces in convection, and for the reliance on artificial plume simulations. Ironically, Henri Bénard's famous convection experiments, characterised by sinking sheets and rising plumes, were not initiated by internal buoyancy forces, as calculated by Lord Rayleigh, but by surface tension forces. It took 50 years to sort that out. One does not win very often by betting against Lord Rayleigh.

As paradoxes accumulate paradigms are eventually abandoned but this takes time. Showing that 'mantle plumes' violate the second law, however, is a sufficient condition to abandon them immediately. Showing that the foundation is composed of logical fallacies is simply another nail in the coffin.

Fallacies

Although violations of physical laws and thermodynamic constraints, and immunity from falsification, are enough to disqualify a mechanism as a physical or scientific theory there are also logical fallacies underlying the plume story. These fallacies have names; Circular Reasoning, Modus Morons, Texas Sharpshooter, Hindsight Heresy, Slippery Slope, False Dilemma, Ratio Fallacy, Ad Hoc Fallacy and so on (Anderson 2002; Cañón-Tapia 2010). They include:

> MORB is from the upper mantle/ therefore, OIB is not.
> Hawaiian basalts are hotter than MORB/ therefore, their source is in the lower mantle.
> MORB represents ambient or average upper mantle/ therefore, OIB is from deeper.
> High $^3He/^4He$ ratios = high ^3He contents = a deep undegassed source.

These represent 'the central dogma' of mantle geochemistry and the bedrock of plume theology (*On this rock I will build my church, and the gates of Hell will not prevail against it*). In geochemistry these are self-evident truths but each is a logical fallacy. Nevertheless, these are the arguments that caused some Earth scientists to shift their attention away from the upper boundary layer into the abyss. The reversal of these arguments does not lead to absurd results.

Other arguments include:

> Temperatures increase with depth/ therefore, OIB sources are in the deep mantle.
> Flood basalts erupt in less than one million years/ plumes erupt in less than one million years/ flood basalts are due to plumes.
> Hawaii erupts at the end of a volcanic chain/ volcanic chains are indicators of deep mantle plumes.
> Fluid dynamics requires the existence of plumes/ fluid dynamics requires that hotspot volcanoes are caused by 'mantle plumes.'
> Ubiquitous components in basalts (C-, FOZO) must derive from depths below the MORB reservoir because they are common components.

Obviously, these are not logically valid (the conclusions do not follow the premises) but the conclusions are often used as arguments for the existence of mantle plumes. In some of the above cases, the premises are also wrong.

Examples of the *Pick-and-Choose, Either-Or* and *Argument from Authority* or *Assertion* and *Red Herring Fallacies* also underlie the plume paradigm (see Anderson 2002; Courtillot *et al.* 2003; Hofmann & Hart 2004). For example:

> Let's analyse only volcanic features where a plume mechanism actually makes some geological sense.
> Volcanic chains are due to either propagating cracks or deep mantle plumes.
> For many geoscientists, the mantle plume model is as well established as plate tectonics.
> Many natural phenomena have been deduced correctly from indirect effects before they could be verified directly.

Although the literature suggests otherwise, isotope geochemistry cannot deliver the silver bullet for proving or disproving plumes, and deep mantle plumes are invisible to seismic tomography. Geochemists refer to seismological studies as having provided, or the potential to provide, the crucial proof that deep plumes exist (DePaolo & Manga 2003; Hofmann & Hart 2004). They suggest, however, that the absence of evidence for plumes in well-constrained seismic images is not evidence for the absence of plumes but is due to poor resolution '*since it is known that plumes are narrow.*' Wave front healing actually renders deep plumes, and narrow slabs, seismically invisible (Hwang *et al.* 2011). Seismologists, who interpret ambiguous colour images in terms of plumes, often refer to geochemical data, usually high $^3He/^4He$ ratios, as supporting evidence for their (non-unique) interpretations (e.g. Humphreys & Schmandt 2011), or consider it surprising that these ratios do not 'agree with seismological interpretations' (Montelli *et al.* 2004).

Finally, there are the *Ratio*, *Bait-and-Switch* and *Moving-the-Goalposts* fallacies. Low *relative* seismic wave-speeds have been erroneously (see Bastow 2012 and references therein) interpreted in terms of plumes or fossil plume heads, and high *absolute* temperatures; but even lower wave-speeds in hotspot-free areas of the subplate mantle, and in the LVL, have been attributed, by mantle jet advocates, to small grainsize rather than to high ambient temperature, which would make hot jets unnecessary. It has been suggested that only seismology can settle the question of whether plumes exist but repeated failures of well-constrained seismic studies to detect plumes have been attributed by plume advocates to failures of the seismic method rather than to the absence of plumes. The well-known helium-paradox is another example of the ratio fallacy.

At one time, proof of plumes was thought to be fixity of hotspots, existence and parallelism of island chains, existence of spreading ridges (which would close down if plumes were turned off), independence from surface tectonics (at least for the few 'midplate' volcanoes that are not controlled by plate boundaries, rifts and fracture zones), age progressions, duration of volcanism, high heat flow, thin lithosphere, precursory uplift, 'primordial' isotope ratios and high ^3He contents and that the idea had been confirmed by laboratory experiments and mantle tomography. All of the above have been used, at one time or another, as evidence but certainly not as extraordinary, unambiguous or non-controversial evidence, to support the hypothesis. *Pluma theologia* now invokes none of these (Courtillot *et al.* 2003; Morgan & Phipps Morgan 2007); selective combinations of non-thermal and circular-argument criteria ('*those that make geological sense*') are now used as plume diagnostics, a different combination for each hotspot. There are multiple contradictory mutually exclusive explanations even for single hotspots, including Hawaii (e.g. Sobolev *et al.* 2005, 2011; Torsvik *et al.* 2010; Ballmer *et al.* 2011; Weis *et al.* 2011; Cottaar & Romanowicz 2012; plus Anderson & Natland 2005 and Cao *et al.* 2011, and references therein).

APPENDIX 2

APPROXIMATIONS IN MANTLE DYNAMICS

Role of lattice dynamics in mantle physics and geodynamics

Planetary interiors involve large changes in pressure and volume and this brings classical and high-pressure physics into mantle convection equations; 'approximations' that assume constant properties or that allow density and viscosity to vary independently of other properties are invalid. These are not 'approximations' to the physics; they are unphysical and unjustified simplifications that often result in a perpetual motion machine. Fluid-dynamic, lattice-dynamic and dimensionless scaling relations are all involved in the internal dynamics and thermal evolution of planets.

The classical views of plate tectonics and volcanoes as stress-controlled, top-down, shallow geological process can basically be understood with mechanics, seismology, rock physics and petrology. Tectonics and volcanoes probably do not involve deep-Earth, or high-pressure condensed-matter, physics (Anderson 2012a). However, appreciation of the effects of secular cooling, radioactivity, self-compression and scale, and the physics of Walter Elsasser, Francis Birch, Max Born, Peter Debye and Eduard Gruneisen are required if one wants to invoke deep mantle processes and, at the same time, avoid fundamental and fatal errors such as occur in existing models of mantle dynamics and geochemistry. It is impossible to intuit from colour images, isotopes and laboratory simulations how the deep Earth and large planets work (Birch 1952, 1965; Anderson 2007a).

Birch noted that words such as *'dubious'* and *'vague suggestion'* become *'undoubtedly'* and *'positive proof'* when applied to deep-Earth theories and this also applies to stories about volcanoes that use deep Earth reservoirs and processes. Assertions such as *'it is now well established that oceanic plates sink into the lower* *mantle'*, *'plumes are as well established as plate tectonics'* and *'geophysical evidence confirms that the lower mantle flows into the asthenosphere',* plucked from the recent geochemical literature, are examples of Birch's high-pressure transformation of ordinary language. These assertions are directly contradicted by quantitative analysis of seismic models (e.g. Hwang *et al.* 2011; Ritsema *et al.* 2011).

'If plumes are not the answer, what is?' From a physics point of view, one can ask *'If plumes are the answer, what is the question?'*

Heat flow into the base of the mantle is an order of magnitude less than into the base of the upper boundary layer and part of it is not used to raise or maintain the temperature since it must be used as work against high pressure. The atoms at the base of the mantle are much closer together than at the surface. The net result is that it is hard to trap heat, to raise temperature and lower density of the deep mantle, and 'impossible' (statistically improbable) to create narrow Rayleigh–Taylor instabilities and fast moving jets without external intervention, such as Maxwell's demon. The effects of radioactivity, secular cooling and compression suppress the formation of narrow buoyant plumes in a real planet. The presence of an intrinsically dense iron-rich BAM further stabilises the lower boundary layer. Flow in the deep mantle must be sluggish, broad-scale and dome-like, a theoretical result confirmed by seismology.

Fluid dynamics

For plumes to be a viable mode of convection in an isolated planet requires that they develop spontaneously and that they satisfy the second law of thermodynamics. In the laboratory, and in the computer, plumes are still induced externally (e.g. Ballmer *et al*. 2011). In a closed system, ruled by thermodynamics, heated from within and cooled from above, the usual methods of creating plumes are ruled out. All fluid dynamic arguments for the existence of plumes in the mantle invoke the equivalent of injection or localised heating mechanisms. In some cases the laws of physics are suspended while the plume head is incubating and growing, e.g. gravity and thermal conduction are turned off until one grows and releases the buoyant mass. Fluid dynamic modelling is now capable of simulating convection in an internally heated, cooling, self-compressed planet with high resolution and self-consistent thermodynamics. As expected from first principles, features resembling mantle plumes do not form in such simulations.

Even in close-to-realistic simulations of mantle dynamics, internal boundaries are usually kept at constant temperature and the mantle is not allowed to self-organise or even to control its own temperature (Schuberth *et al.* 2009). This violates the laws of thermodynamics and fluid dynamics at several levels. And the models do not even explain the global seismic data that motivated the calculations.