The mantle plume debate in undergraduate geoscience education:

Overview, history, and recommendations

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ABSTRACT

Mantle plume theory has been widely, but not universally, accepted in the geosciences for several decades, but recent critical evaluation has led to an intense debate regarding the existence of mantle plumes. I provide an overview of mantle plume theory and the current skepticism. The results of a poll taken after the 2005 AGU Chapman Conference, “The Great Plume Debate” are presented to give general readers a sense for which arguments specialists consider to be strongest in favor of, or opposing, mantle plume theory. Mantle plume theory first appeared in introductory textbooks in the late 1970s, and the theory was presented in most introductory textbooks by the end of the 1980s. In light of the current debate most recent editions have introduced language indicting debate and uncertainty about mantle plume theory. However, none of these textbooks offers any alternative hypotheses; advanced textbooks also give little attention to alternative hypotheses. I assert that, without the presentation of alternative theories, students will simply accept the one presented as fact. The current debate should be seen as a teaching opportunity. It should be conveyed to students that this debate reflects the fact that geology is a very dynamic science and that first-order problems remain in the geosciences to be addressed by current and future generations.

INTRODUCTION

In most introductory geoscience textbooks, mantle plume theory is presented as the explanation for age-progressive intraplate volcanism (e.g., Hawaii) and anomalous plate margin volcanism (e.g., Iceland) in most introductory geoscience textbooks. Mantle plume theory is also presented in textbooks for relevant upper-division courses, such as igneous petrology and structural geology/tectonics. While mantle plume theory has been widely accepted in the geoscience community for several decades, there were skeptics from the beginning, and the last decade has seen revitalization of critical evaluation of mantle plume theory, the development of alternative theories, and vigorous debate of the subject. The purpose of this paper is to examine the current, and historical, presentation of mantle plume theory in undergraduate geoscience courses, and to make recommendations to undergraduate educators and textbook authors for treatment of the mantle plume debate at the undergraduate level. As the target audience for this paper includes non-specialists, I will open with a brief introduction to mantle plume theory and the current debate; for more extensive reviews from both sides of the debate see articles from plume-advocate perspective by Davies (1999, ch. 13; 2005), Sleep (2006; this volume), and Campbell (2006), or from the plume-skeptic perspective by Anderson and Natland (2005) and Foulger (2005, this volume).

Mantle Plume Theory

In the midst of the plate tectonic revolution, J. Tuzo Wilson (1963, 1965) introduced the concept of hotspots as an explanation for intraplate volcanism (e.g., Hawaii) and anomalous plate margin volcanism (e.g., Iceland), phenomena which were generally considered to be without simple explanation in the evolving plate tectonic model. The hotspot model postulated the presence of unusually hot mantle underlying these areas of persistent anomalous volcanism but did not propose a mechanism for their origin. The term "hotspot" is now used generically to refer to areas of anomalous volcanism without implying a process, the term "melting anomaly" is also used in this way and has the advantage of not implying anomalously high temperature, a contested point in the debate. Jason Morgan (1971, 1972a,b) proposed mantle plume theory as an explanation for hotspots. Morgan postulated that hotspots could be surface manifestations of thermal plumes in the mantle, and that such plumes would arise from the core-mantle boundary, the most significant thermal boundary layer in the interior of the Earth.

The plumes that Morgan envisioned were essentially vertical features, fixed with respect to one another. This original mantle plume theory has been appended and modified in a number of ways. Many modifications have been criticized as being *ad hoc* (e.g., Anderson, 2000); the fact that the theory is susceptible to *ad hoc* modification is recognized by many of its proponents (e.g. Sleep, this volume). However, many modifications are based upon reasonable, though not definitive, models of the properties of the interior of the Earth. In as much as these models constitute significant changes from the Morgan (1971, 1972a,b) model they should properly be considered distinct alternative theories, testable aspects should be identified, and the theories should be evaluated. This paper addresses mantle plume theory in a broad sense as consisting of a family of theories spawned from Morgan's original model.

Mantle plume theory, restricted to the original definition of Morgan (1971, 1972a,b), has already been disproved by the demonstration that hotspots are not fixed with respect to one another (e.g. Molnar and Stock, 1987). A model has been proposed by Steinberger and O'Connell (1998, 2000) that is not *ad hoc* that may account for non-fixity of hotspots. They impose a mantle structure based on seismic tomography and allow that structure to dictate flow then model the effect of this flow on rising plumes. The parameters of the model may be contested, but it is predictive, and not *ad hoc*. Two other important addenda or modifications include:

(1) Mantle plumes originating with plume heads which give rise to large igneous provinces (flood basalts) (e.g. Morgan, 1981; Richards et al., 1989; Griffiths and Campbell, 1990; Campbell and Griffiths, 1990).

(2) Thermo-chemical plumes, in which buoyancy may arise from compositional heterogeneity in addition to temperature, have been modeled by Farnetani and Samuel (2005). The results suggest a more diverse array of plume forms. Testable aspects of this model should be identified and considered.

Beyond age-progressive volcanism, evidence that plume-advocates commonly consider to be in support of mantle plume theory include: common association with flood basalts, distinctive isotopic signatures (including helium), topographic swells and geoid highs, seismic tomography, and the results of analog and numerical modeling. It is important to note that all of these lines of argument have either been used by plume-skeptics to argue against a plume origin or addressed in their arguments (e.g. Foulger, 2005, this volume; Anderson and Natland, 2005).

Plume Skepticism and Alternative Hypotheses

According to Anderson and Natland (2005) mantle plume theory was received with considerable skepticism when it was proposed in the early 1970s. Early criticism of mantle plume theory was based on a variety of arguments and lines of evidence including fluid dynamics, geophysical data, and other observations. The subject was controversial enough that it was one of several topics chosen for selected-readings coverage in the Cowen and Lipps (1975) volume, *Controversies in the Earth Sciences*.

For most of the 1980s and 1990s, as mantle plume theory was reinvigorated in the wake of publication of analog and numerical modeling results and the application of these models (e.g., Richards et al., 1989), critical evaluation diminished. Several leading researchers, notably Don Anderson (e.g., Anderson et al., 1992), continued to critique the theory and seek alternatives. Skeptical analysis of mantle plume theory at the beginning of the 21st century. Through several conferences and the catalyzing efforts of Gillian Foulger in the development of the www.mantleplumes.org website, a cohesive and active community developed to focus on the critical evaluation of mantle plume theory and the development and advancement of alternative theories.

The criticisms of mantle plume theory are founded on a number of points, including the following (not intended to be exhaustive):

(1) That hotspots are not hot, with no abnormal heat flow (e.g., Stein and Stein, 2003) or indication of high magmatic temperatures (e.g., Green and Falloon, 2005).

(2) That helium isotope ratios considered characteristic of mantle plumes are not due to high ^3He, and could be generated at shallow depths (e.g., Anderson, 2000; Meibom

and Anderson, 2004); other isotopic characteristics also can be explained by shallow processes (e.g., Anderson and Natland, 2005).

(3) Most hotspots do not meet standard criteria for mantle plumes, commonly age-progressive volcanic track, originating with flood basalt, high buoyancy flux, high maximum $^3He/^4He$ ratios, and a low-velocity anomaly in tomographic images (e.g., Courtillot et al., 2003; Anderson, 2005).

(4) Seismic tomography indicates no plume in the lower mantle beneath many postulated plumes (e.g., Foulger et al., 2001), and many seismic tomography images showing lower mantle plumes saturate the images, creating misleading results.

(5) Durations of volcanism and the relationship between large igneous province development and extension favor lithospheric processes for the development of these provinces (e.g., Sheth, 2000).

(6) When a locale fails to conform to standard criteria (e.g., criteria of Courtillot et al., 2003, and Anderson, 2005) for mantle plumes *ad hoc* modifications to the theory are made, rendering the theory untestable (e.g., Foulger, this volume).

(7) Simpler models can be developed based on shallow plate tectonic processes (e.g., Anderson, 2001; Hamilton, 2003; Foulger, this volume).

Many of the above-listed assertions are contested by plume-advocates. To read more thorough recent accounts from both sides see Davies (2005) and Foulger (2005).

Alternative hypotheses for hotspots had been around prior to the proposal of mantle plume theory, and more were suggested in the 1970s. The early history of alternative theories includes propagating cracks, shear melting, self-perpetuating volcanic chains, membrane stresses, and gravitational anchors; see Anderson and Natland (2005) and references therein for more detailed discussion of these developments. Along with the renewed critical evaluation of mantle plume theory that arose at the beginning of the 21st century have come a number of new or revived alternative hypotheses for the origin of hotspot volcanism. These models have in common the interpretation of relatively shallow (lithospheric or upper mantle) processes responsible for hotspots. The alternative models can be grouped in four categories: increased fertility for melting (e.g., Foulger and Anderson, 2005; Foulger et al., 2005a for Iceland); fractures tapping magmas already present at depth (e.g., Hamilton, 2003); shallow convection (e.g., edge-driven convection of King and Anderson, 1998); and extra-terrestrial mechanisms (e.g., Hagrstrum, 2005). The first three mechanisms share the interpretation of hotspots as a second-order effect of plate tectonics, the "plate" model of Foulger (this volume).

Current Status of the Debate

Following the 2005 American Geophysical Union Chapman Conference, "The Great Plume Debate", I conducted an online poll of participants, as well as those who had expressed interest but not attended. Some of the results may be interesting for non-specialists trying to understand the issues involved in the debate. Before presenting the results, two caveats should be noted. This conference brought together people from both sides of the debate; thus, the unfiltered results are not reflective of overall opinion in the relevant fields in the geosciences. Second, the total number of respondents is not large, and filtered results have a smaller n; this was not a scientific poll, though I attempted to conduct it without bias. Poll participation requests were sent to 107 people, and 66 responded (62%). There were twelve questions in the poll, five of which are discussed in this paper, in the following paragraphs and the recommendations section.

The first question was a multiple choice question intended to ascertain the participants' positions in the plume debate. The question, choices offered, and results are presented in Table 1. The five available choices were written to offer strong and moderate, pro-plume and plume-skeptical responses as well as a middle-of-the-road response. The results of this question were used to filter all other results into three groups for further analysis, plume-advocate (first and second responses), middle (third response), plume-skeptical (fourth and fifth responses). It is a credit to the conveners (who represented both sides) that the results to this question were so balanced with 29% plume-advocate, 24% skeptical, and the remainder in the middle. Another poll result that speaks in favor of the kind of dialog represented by this conference is that 70% of respondents who attended the conference reported that their answer to this question changed because of something they heard at the conference.

Two questions were asked to identify which observations, data, or lines of argument the participants felt most strongly supported or opposed mantle plume theory. Eight choices were provided for each question, encompassing a selection of the main arguments commonly offered by both sides, as well as a none-of-the-above response. Participants could select more than one choice. These questions, responses, and results are summarized in Table 2. These results are presented in-full and filtered; the filtered responses are particularly interesting.

Age-progressive volcanic chains are identified as the strongest line of evidence supporting mantle plume theory in the unfiltered results and in each of the three filtered groups, including 40% of the plume-skeptics. This is not a surprise as this was one of the primary observations leading to the concept of hotspots (Wilson, 1963) and the development of mantle plume theory (Morgan, 1971, 1972a,b). Results of seismic tomography, the relationship with large igneous provinces (flood basalts), and the results of modeling were also indicated by >40%

of respondents in the unfiltered results and the plume-advocate, and middle groups. Interestingly, the order of the top seven responses was the same in the unfiltered, plume advocate, and middle groups. The relatively unsatisfying response, no other viable explanation received low, but approximately equal in all groups, support.

In the unfiltered results the argument indicated as most strongly arguing against mantle plume theory was that many proposed plumes do not meet standard criteria for plumes; this was also the leading selection of the plume-advocate and middle groups. Inconsistencies or problems, other than non-fixity (which was another choice), with hotspot tracks was the only other response identified by a significant number of plume supporters. The middle group also identified lack of evidence of high temperature and geochemical signatures more easily explained by other processes as significant. Plume-skeptics rated all of the arguments against mantle plume theory, other than seismic tomography, pretty highly. The single response that received the most support from this group was the lack of evidence for high temperatures.

An interesting result of the poll, considering the unfiltered data, is that the lines of evidence are seen as significant arguing both ways. Evidence of high magmatic temperatures rated a 30% in support of mantle plume theory, and lack of evidence for high temperatures rated a 33% against plume theory. These mutually exclusive responses suggest promise for resolution, as apparently both sides have made compelling, but not convincing, arguments with regard to temperature. Geochemical arguments also went both ways in approximately equal proportion (supporting plumes: helium isotopes 21%, and other signatures 25%; against plumes: geochemical signatures more easily explained by other processes 27%). This area offers less short-term promise of resolution as the chemical arguments are largely model-driven on both sides.

Hierarchy of Theories and the Standing of Mantle Plume Theory

Theories originate as hypotheses, logical explanations of observations, subject to subsequent testing. The boundary between hypothesis and theory is not clearly defined, but generally, when a hypothesis is supported by subsequent observations, and becomes widely accepted, it is elevated to the level of a theory. To have a framework within which to discuss the standing of mantle plume theory it is useful to have a defined hierarchy of theories. A useful classification scheme is that of Dutch (1980), who described a three-tiered hierarchical classification of theories: central, frontier, and fringe. Dutch (1980) classifies hypotheses as fringe theories; most do not stand the test of time and will be discarded. Some theories are supported but have unresolved inconsistencies and/or serious alternatives; these are frontier theories which constitute the mainstream thinking of a scientific discipline. Central theories are no longer seriously disputed, and form the foundation of a discipline.

Twenty-five years ago, Dutch (1980) considered plate tectonic theory to be at the central/frontier transition. At present, plate tectonics is a central theory in geology. Mantle plume theory is commonly regarded as a fundamental addendum to plate tectonic theory, and might seem to therefore also hold the status of a central theory. However, the current vigorous debate about the existence of plumes suggests that mantle plume theory is more properly regarded as a frontier theory. This classification is also consistent with the fact that even among plume-advocates there are differing views about the nature and origin of plumes (e.g., Courtillot et al., 2003; Montelli et al., 2004, 2006; Farnetani and Samuel, 2005). Many plume-skeptics would consider it a disproved hypothesis, or fringe theory

PRESENTATION OF MANTLE PLUME THEORY IN UNDERGRADUATE TEXTBOOKS

Hotspots are a first-order planetary scale phenomena of the Earth, and most textbooks dealing with the Earth on a large scale, or addressing topics directly relating to hotspots, must address their origin. The following questions are addressed here. How are hotspots explained in undergraduate geoscience textbooks? Does the explanation reflect the current debate about the origin of hotspots? What is the history of presentation of mantle plume theory in introductory textbooks?

Mantle Plume Theory in Current Introductory Geology Textbooks

Below are quotations from several commonly used introductory textbooks regarding hotspots and mantle plumes. These brief quotations are chosen to try to reflect the various presentations of mantle plumes and, particularly, the degree of uncertainty in mantle plume theory that is expressed in the recent texts. A general discussion follows the quotations.

Press et al. (2004)

> *"Almost all geologists accept the notion that hot-spot volcanism is caused by some type of upwelling in the mantle beneath the plates. However, the mantle plume hypothesis--that these upwellings are narrow conduits of material rising from the deep mantle--remains controversial."*

And later, discussing plume heads as the cause of flood basalts, *"Others dispute this hypothesis, pointing out that continental flood basalts often seem to be associated with preexisting zones of weakness in plates--suggesting that the magmas are generated by convective processes in the upper mantle."*

Hamblin and Christiansen (2004)

"We are not completely sure, but the simple idea of mantle plumes rising as narrow columns from the deep interior explains many such features [hotspots] and has become a generally accepted part of plate tectonic theory."

Tarbuck and Lutgens (2005)

"We now recognize that most intraplate volcanism occurs where a mass of hotter than normal mantle material called a mantle plume ascends toward the surface. Although the depth at which (at least some) of these mantle plumes originate is still hotly debated, many appear to form deep within the Earth at the core-mantle boundary."

Marshak (2005)

"Most mantle plumes are thought to originate just above the core mantle boundary, where heat from the Earth's core warms the base of the mantle. (Recent evidence, however, suggests that some may originate in the upper mantle.)"

Smith and Pun (2006)

"The plume hypothesis for explaining hot spots is not yet adequately tested and is very controversial. It is possible that not all hot spots have the same origin."

Chernicoff and Whitney (2007)

"Some geologists believe that these partially melted zones may be the sources of great plumes of rising hot mantle that may be driving the motion of the Earth's plates and

fueling the volcanism that occurs at intraplate hot spots such as the Hawaiian Islands and Yellowstone National Park."

Plummer et al. (2007)

""Hot spots" in the crust (where the geothermal gradient is locally very high) have been hypothesized to be due to hot mantle plumes, which are narrow upwelling of hot material within the mantle."

And later,

"However, researchers using new data have questioned the extent, and even the existence, of deep mantle plume. (For an in-depth discussion on the debate about mantle plumes, go to www.mantleplumes.org/.)"

The quotations above do express some uncertainty about the uniformity of plumes and their depth of origin, and some convey a sense of scientific debate of the issue. The treatment in most of these texts suggests a status of frontier theory, in the usage of Dutch (1980), for mantle plume theory. However, a critical point is that all of these recent texts go on to explain mantle plume theory in detail, and none offers an alternative hypothesis.

History of Presentation of Mantle Plume Theory in Introductory Textbooks

Mantle plume theory began to appear in introductory textbooks in the late 1970s. Press and Sevier (1978) included an introduction to mantle plumes, which they appropriately described as a "controversial concept", in their second edition; the first edition, published four years earlier, did not include a reference to mantle plumes. Several current introductory textbooks have editions dating back to the 1970s and early 1980s. Hamblin and Christiansen (2004) dates back to 1975. The first edition (Hamblin, 1975) uses the term plume to describe hotspots, but does not indicate a lower mantle origin. By the fifth edition (Hamblin and Christiansen, 1989), they identify plumes as arising from >700 km depth and state, "… the simple idea has become a generally accepted part of plate tectonic theory."

The text by Plummer et al. (2007) traces back to 1979. By the second edition (Plummer and McGeary, 1982; a first edition was not available for review), mantle plume theory was described with frequent references to Morgan, and plumes were depicted as originating at the core-mantle boundary. This was followed by a note of skepticism, *"Deep-sea drilling has shown, however, that not all aseismic ridges increase in age along their lengths. This evidence has led to alternate hypotheses for the origin of aseismic ridges. It may pose difficulties for the plume hypothesis itself."* Interestingly, that exact text remains in the current edition.

The Tarbuck and Lutgens (2005) text was first published in 1985. The first edition, Tarbuck and Lutgens (1985) explained hotspots as, "…plumes of molten rock that rise from deep within the mantle", but they were not explicit about a depth of origin for these plumes.

So mantle plumes have been offered as an explanation for hotspot volcanism in introductory textbooks for two to three decades. Press and Sevier (1978) treated mantle plume theory as a fringe theory, in the usage of Dutch (1980), a treatment appropriate for the time. Other authors treated mantle plume theory as a frontier or central theory. Anderson (2005) describes interest in plume-related research as being "steady but low" through the 1980s – ironically, it is this decade that mantle plume theory became a fixture in most introductory textbooks. Most authors have made changes in their most recent editions of their textbooks to better reflect the current debate over mantle plumes. But, again, none offers any mention of proposed alternatives.

Other Introductory Geoscience Courses

Many students take other closely related introductory geoscience courses such as environmental geology, which is often an accepted substitute for physical geology in American geology departments, or Oceanography. Several quotations from texts in these subjects are provided below.

Environmental Geology:

Thompson and Turk (2005)

> *"In contrast to the huge curtain-shaped mass of mantle that rises beneath a spreading center, a mantle plume is a relatively small rising column of hot, plastic mantle rock. Many plumes rise from great depths in the mantle, probably because small zones of rock near the core-mantle boundary become hotter and more buoyant than surrounding regions of the deep mantle. Others may form as a result of heating in shallower portions of the mantle."*

Oceanography:

Pinet (2003)

> *"These volcanic mountains [the Hawaiian Islands and seamounts] are created over a deep-seated "hot spot" called a mantle plume. Mantle plumes are places where molten rock originates deep below the asthenosphere."*

Both quotations provided above state mantle plumes as a fact though Thompson and Turk (2005) do indicate that some may be shallow features. These texts clearly treat mantle plume theory as a central theory in the hierarchy of Dutch (1980). Some oceanography and environmental geology textbooks simply do not take the discussion any further than hotspots. It is inevitable that textbooks for geoscience subjects that are less focused on internal Earth processes, such as such as these, have to give more brief coverage to subjects like hotspots and mantle plumes. It will commonly be necessary to simplify the treatment of complex or controversial issues in these texts. However, changes in language to indicate that mantle plumes are hypothesized or theorized would require only minor modifications.

Upper Division Courses

Explanations for the underlying causes of hotspot volcanism are generally presented in petrology textbooks. Mantle plume theory is also touched on in some textbooks used for other upper division courses such as structural geology, geophysics, and volcanology. Below I provide quotations from two leading current petrology textbooks for consideration.

Winter (2001)

> *"Island chains in the same plate follow subparallel paths and progress in the same direction, leading Wilson (1963) to conclude these chains were the result of volcanism generated by hot spots, or rising plumes generated by thermal anomalies originating in the deep mantle (or even the core), and thus anchored in place beneath the moving plates."*
>
> And later,
>
> *"Explanations for hot spots include thermal perturbations in the deep mantle or core, compositional plumes of less dense material (Anderson, 1975), and volatile influx causing melting point reduction and rise of buoyant melts."*

Best (2003)

"First proposed by Morgan (1971), mantle plumes had been confirmed to exist by the end of the century through seismic tomography imaging (see, for example, articles in the March 19th, 1999, and May 14, 1999, issues of Science)."

And later,

"The proposal of Wilson (1963) that the [Hawaiian Island-Emperor Seamount] chain originated by the movement (at that rate [8-9 cm/y]) of the oceanic lithosphere over an essentially stationary mantle plume is now accepted by most geologists".

Winter (2001) has been cautious to be descriptive of the literature on the subject rather than stating his own conclusions, and in doing so even mentions alternative hypotheses, though he does not go into them in any depth. The first quotation from Best (2003) is one that would be contested by most plume-skeptics. The second *Science* article referred to by Best (2003) summarizes the tomography of Bijwaard and Spakman (1999) for Iceland. Subsequent tomographic studies suggest that the low-velocity anomaly under Iceland is either entirely limited to the upper mantle, arguing against a mantle plume (e.g. Foulger et al., 2001), or only weak and discontinuous in the lower mantle suggesting a "pulsating plume" (Montelli et al., in press). The statement made in the second quotation is true, though the citation of Wilson (1963) is incorrect as he did not propose a mantle plume.

RECOMMENDATIONS

Mantle plume theory is a frontier theory, in the usage of Dutch (1980). It should be treated as such in undergraduate textbooks, and taught that way in undergraduate classrooms.

Through either direct reference to debate or the use of terms like "hypothesized", the current field of introductory texts does a pretty good job of reflecting the present debate regarding mantle plumes. The fact of the matter is that even amongst the plume-advocate community there are divergent views about the nature of plumes, so an expression of uncertainty about the theory is appropriate. However, in the thirty-five years since the proposal of mantle plume theory no introductory textbook that I have found has ever discussed an alternative hypothesis.

When first exposed to the debate over mantle plumes as an explanation for hotspots, the first question most people ask is, "what else could they be?" I believe that this is because, even if textbooks express some uncertainty regarding a theory, if no alternative theory is proffered then the reader has little option other than to accept the presented theory. This is especially true in introductory courses, which generally emphasize transmission of facts and concepts rather than critical thinking; there is, after all, a tremendous amount of material to be covered in these courses.

I strongly recommend that textbook authors complement the current, often detailed, description of mantle plume theory with at least a paragraph introducing the fact that there are alternative hypotheses, and exploring at least one in some depth. The more detailed description of an alternative hypothesis could be done by considering an alternative model applied to a specific location, such as the model for Iceland proposed by Foulger and Anderson (2005) and Foulger et al. (2005a). Even in the absence of the presentation of such a model in a textbook, instructors could introduce an alternative hypothesis in lectures. My argument is that this would lend legitimacy to what I hope all, no matter what side of the debate they are on, would agree is appropriate language in these textbooks, treating mantle plume theory as a frontier theory, a work in progress, contested by some.

Some may feel that the debate over mantle plume theory is too complex to explain to introductory students. However, introductory students are taught that melting within the Earth can result from heating, decompression, or adding water and decreasing the melting point, so that hotspot magmatism could result from something other than unusually hot mantle should be within their grasp. The poll conducted in the wake of the Great Plume Debate Chapman Conference, asked participants if they considered the debate over mantle plume theory to be to complex to explain to introductory students. The question, choices, and results, are presented in Table 3. Only 10%, overall, considered the mantle plume debate to be too complex for the introductory classroom. Interestingly, it is the plume-skeptics who had the greatest concern that the subject may be too complex. The leading response (70% overall) was that the issue was not too complex and should be introduced in introductory classes; this was the leading choice among each group, though among plume-advocates it was tied with the response that it was not too complex, but it was unnecessary because the theory is sound.

In related geoscience courses, such as oceanography and environmental geology, the approach taken by current textbooks is understandable, but could be improved. Current texts either skip the issue by leaving anomalous volcanism as the result of hotspots, or present mantle plume theory as fact, as a central theory. All that would be required to more accurately reflect the status of the debate would be to change a word or two to include language like “theory” or “hypothesis”.

Upper division courses are actually in the best position to benefit from more thorough discussion of the mantle plume debate. Courses like petrology, tectonics, and geophysics could explore the debate by considering the relevant data and observations deriving from these fields and exploring how they bear on the debate. In this perspective, the current treatment of the mantle plume debate in some petrology textbooks is disappointing. I would encourage textbook authors to present alternative hypotheses, though as mantle plume theory is favored in the discipline an emphasis on this theory is still appropriate. As with introductory classes, I recommend first covering the alternative hypotheses broadly, then exploring at least one in depth as applied to a specific locale.

I would encourage educators and textbook authors to remain abreast of developments in this debate and the rapidly evolving ideas on both sides. I would, however, caution them to approach the literature seeking balance. This can be difficult. Much of the mainstream literature on locations where plumes have been invoked ignores the debate and alternative hypotheses. On the other side, Foulger et al. (2005b) and the website www.mantleplumes.org are resources mostly dedicated to the exploration of alternative hypotheses. As neither the mainstream literature nor these other resources alone provide a balanced presentation of the debate, it may take some effort on the part of the reader/researcher to find balance. The mantle plume theory, its modifications, and alternative hypotheses should all be subject to the same high standard of critical evaluation. If the scientific method works properly the current debate will either result in disproving mantle plume theory or the evolution of a stronger, more robust, mantle plume theory.

Mantle plume theory, as generally taught in the classroom, is a simple, elegant theory that explains the magmatism that plate tectonics does not. It is, therefore, appealing to treat it as an addendum to plate tectonics and give it the status of a central theory in the classroom. However, we are doing the students a disservice by doing so, and, by not encouraging open minds and critical thinking, perhaps doing damage to the future of our own science. The mantle plume debate offers an opportunity to demonstrate to students, at all levels, that the geology is a dynamic science, still addressing first-order questions about how the Earth works, research that they could be involved in if they choose.

ACKNOWLEDGMENTS

I am grateful for funding from the American Geophysical Union which supported my attendance of the 2005 Chapman Conference, "The Great Plume Debate". I thank the conveners and participants in that conference for a lively and productive discussion, and in particular I appreciate the time many took to complete my online poll, for which results are presented here. I thank the Robert Tilling, Steven Marshak, and Gillian Foulger for constructive reviews of this manuscript.

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TABLE 1. POLL RESULTS - VALIDITY OF PLUME THEORY

Question/Responses	Votes	%
Question: Which of the following best describes your perspective on the debate regarding mantle plume theory?		
Most intraplate volcanism and anomalous plate margin volcanism can be explained by mantle plume theory; mantle plume theory is well supported by observations, data, and modeling.	0	0%
Most large systems of intraplate volcanism and anomalous plate margin volcanism can be explained by mantle plume theory; mantle plume theory is well supported by observations, data, and modeling at these sites. Smaller systems may be explained by other processes.	19	29%
Mantle plume theory is a generally viable model for most large systems of intraplate volcanism and anomalous plate margin volcanism, but there are unresolved inconsistencies in observations, data, and modeling; alternative models should be developed and tested.	30	46%
Mantle plume theory has many inconsistencies with data and observations and is probably not a viable explanation for intraplate and anomalous plate margin volcanism; most data and observations are more consistent with shallow (lithospheric and upper mantle) processes.	12	18%
Mantle plume theory has been disproved; intraplate volcanism and anomalous plate margin volcanism are best understood as the result of shallow (lithospheric and upper mantle) processes.	4	6%

TABLE 2. POLL RESULTS - ARGUMENTS FOR AND AGAINST MANTLE PLUME THEORY

Questions/Responses	All	Plume Advocates	Middle	Plume Skeptics
Question: Which of the following do you feel most strongly argue for mantle plume theory? (you may select more than one)	*n=61*	*n=18*	*n=28*	*n=15*
Age-progressive volcanic chains	**72%**	**89%**	**79%**	**40%**
Seismic tomography	48%	67%	57%	7%
Large igneous provinces	43%	67%	50%	0%
Numerical and analog models show plume formation	43%	56%	46%	20%
Evidence for high magmatic temperatures	30%	44%	36%	0%
Isotopic (other than helium) and trace element signatures	25%	44%	25%	0%
Helium isotope ratios	21%	39%	21%	0%
No other viable explanation	5%	6%	4%	7%
None of the above, I believe that mantle plume theory is not supported by observations, data, and modeling.	15%	0%	4%	53%
Question: Which of the following do you feel most strongly argue against mantle plume theory? (you may select more than one)	*n=60*	*n=16*	*n=28*	*n=16*
Many plumes don't meet standard criteria for plumes	**47%**	**31%**	**54%**	50%
Inconsistencies or problems (other than non-fixity) with hotspot tracks	37%	19%	36%	56%
Lack of evidence for high temperatures	33%	0%	32%	**69%**
Geochemical signatures more easily explained by other processes	27%	0%	32%	44%
Relationship between large igneous province development and extension	23%	6%	14%	56%
Hotspots not fixed with respect to one another	20%	0%	18%	44%
Poor application of the scientific method in support of mantle plume theory	20%	0%	14%	50%
Seismic tomogrpahy	17%	6%	18%	25%
None of the above I believe that mantle plume theory is strongly supported by observations, data, and modeling	22%	56%	14%	0%

Note: bold indicates leading answer in for each group

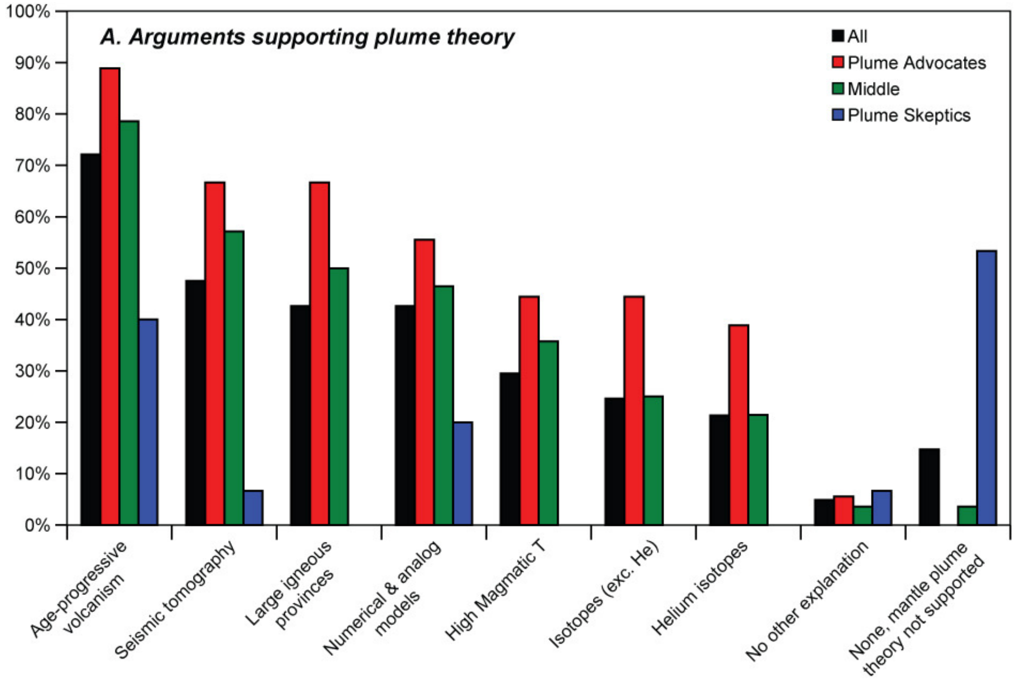
TABLE 3. POLL RESULTS - TEACHING THE MANTLE PLUME DEBATE

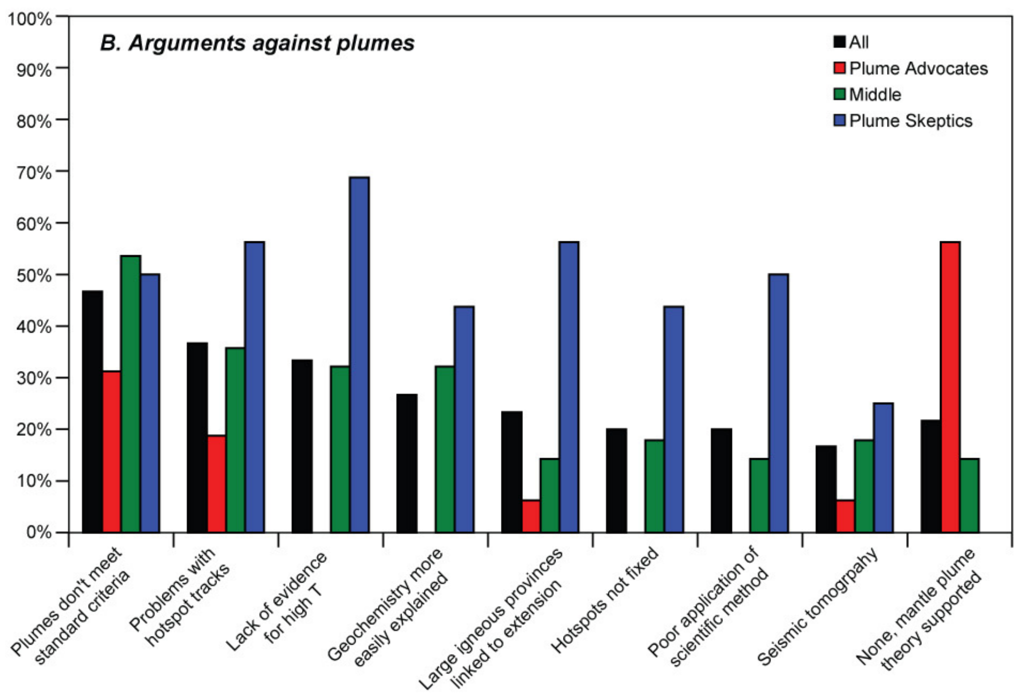
Question/Responses	All	Plume Advocates	Middle	Plume Skeptics
Do you consider the content of the debate regarding mantle plume theory to be too complex for, or difficult to explain to, introductory geoscience students?	n=61	n=15	n=30	n=16
Yes	10%	7%	7%	19%
No, but mantle plume theory is sound enough that presenting the debate is unnecessary.	16%	47%	10%	0%
No, the debate and some alternatives can be taught to introductory students.	70%	47%	83%	69%
No, and as alternatives are more consistent with observations, they should be presented instead.	3%	0%	0%	13%

FIGURE CAPTIONS

Figure 1. Histograms of poll data presented in Table 2, indicating lines of evidence that participants in the 2005 AGU Chapman Conference, “The Great Plume Debate”, identified as most strongly supporting (A), or arguing against (B) mantle plume theory. Data is presented unfiltered and filtered by leaning in the plume debate as discussed in the text.

FIGURE


A. Arguments supporting plume theory
All
Plume Advocates
Middle
Plume Skeptics
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Age-progressive volcanism
Seismic tomography
Large igneous provinces
Numerical & analog models
High Magmatic T
Isotopes (exc. He)
Helium isotopes
No other explanation
None, mantle plume theory not supported


B. Arguments against plumes
All
Plume Advocates
Middle
Plume Skeptics
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Plumes don't meet standard criteria
Problems with hotspot tracks
Lack of evidence for high T
Geochemistry more easily explained
Large igneous provinces linked to extension
Hotspots not fixed
Poor application of scientific method
Seismic tomogrpahy
None, mantle plume theory supported