The extent to which the ^{3}He/^{4}He isotope ratio can be used as a geochemical tracer to localise the source and confirm the existence of mantle plumes at hotspots

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Abstract

In recent debate, the extent to which the $^{3}He/^{4}He$ isotope ratio can be used as a geochemical tracer to localise the source and confirm the existence of mantle plumes at hotspots has become a very controversial issue. In the classic model, a high helium ratio is an indicator for mantle plumes that reach the core-mantle boundary. However, growing evidence suggest that there cannot exist elevated ^{3}He concentrations in the lower mantle. Instead, critics believe that a high $^{3}He/^{4}He$ ratio is due to lower ^{4}He concentrations. The location where these lower ^{4}He concentrations exist has been proposed to be in the upper mantle. This alternative model effectively rules out the need for core-mantle boundary mantle plumes at hotspots.

Much geochemical research and (re-)calculations of He isotope ratios done by scientists has proven that helium is no longer a strong indicator of a primitive and undegassed lower mantle, the source for mantle plumes. For example, Natland (2002) showed that it is possible to trap helium inside inclusions found in olivine phenocrysts. Because olivine normally does not contain any U+Th, the radioactive isotopes for ^{4}He, no extra ^{4}He is produced over time and the initial $^{3}He/^{4}He$ remains the same and consequently higher than at locations where ^{4}He is freely produced existing along ^{3}He. Anderson suggested that the location of these olivine phenocrysts is in a cumulate olivine-gabbroic layer, otherwise known as *restite*, belonging to the lowermost crust.

No actual recent research shows any evidence that high helium ratios do clearly confirm that mantle plumes exist. This, what could be called an assumption, was made in the 1980s and has strongly supported the mantle plume hypothesis for a while. Many models have been created based on this. For example, a box model dealing with the role of plumes in mantle helium fluxes was set up by Kellogg and Wasserburg in 1990. However, from 1997 onward the helium ratio as an indicator for mantle plumes has shown some serious flaws such as why do the ratios often exhibit dramatic temporal en spatial variations at hotspots such as Hawaii? [Anderson, 1999].

The helium isotope ratio is still being used, nevertheless, because it is one of the only geochemical pieces of evidence for mantle plumes. Courtillot et al. (2003) even today uses it as one of the five criteria that prove the existence of core-mantle boundary mantle plumes. There may be one last hope left for high $^{3}He/^{4}He$ ratios confirming the existence of mantle plumes, which is the possibility for high helium isotope ratios to exist at the D” boundary. However, as long as there is no concrete proof for this assumption, backed up by valid calculations, this geochemical tracer is no longer fit to serve as evidence for mantle plumes.

Introduction

High ^{3}He/^{4}He isotope ratios have been particularly interesting especially in the past to confirm geochemically that mantle plumes exist and come from the lower mantle. The evidence originated from the fact that helium ratios from the MORB are typically lower than ratios found at hotspots. In addition, at oceanic ridges the magma source is definitely from the upper mantle. Most scientists agreed in the past without much debate that therefore the higher He ratios must come from a magma source containing excess ^{3}He. This source, called the FOZO[1] [Hart et al. 1992] or PHEM[2] [Farley, et al, 1992], was agreed upon to be located in the lower mantle. Thus because ^{3}He is cosmogenic in origin and can be found in higher concentrations particularly at hotspots, many scientists believe that ^{3}He comes from a primary magma found in the lower mantle deep in the Earth that has not yet undergone mixing or degassing with its surrounding material.

The alternative approach suggests that high He ratios are caused not by an excess of ^{3}He but rather by a depletion of ^{4}He in the upper mantle. The ^{3}He would reside inside inclusions of olivine phenocrysts [Natland, 2003] where noticeably the ^{4}He concentration is low due to the non-existence of U and Th, and thus the ^{3}He/^{4}He ratio is high. This consequently eliminates the need for a primordial undegassed lower mantle reservoir. Therefore, the question remains to what extent the helium isotope ratio can be used as evidence for the existence of hotspot mantle plumes and locating their origin.

In the past much research has been conducted why helium ratios are typically higher in hotspot areas than elsewhere in the world, for example at island arc volcanoes. Helium-3 is a primordial element that originates from the beginning of the solar system. This means that it is a very useful geochemical tracer. ^{3}He can be created in the reaction where ^{6}Li is exited by the capture of a neutron caused during U fission and decays to form tritium (^{3}H) with a beta particle and ^{3}He. However, this reaction is very rare and does not produce a lot of ^{3}He. ^{3}He can also accrete on the Earth surface by interplanetary dust particles and by cosmic rays. Again, this amount is rather insignificant. Helium-4 is a by-product of radioactive decay of Uranium and Thorium and so exists in a much greater concentration. I.e. For every ^{3}He atom, there exist 1.384×10^6 ^{4}He atoms in the atmosphere. For simplicity, He isotope ratios are often related to the atmospheric value by R/R_A, where R is ^{3}He/^{4}He ratio[3] and R_A is the atmospheric He ratio.

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[1] <u>Fo</u>cal <u>Zo</u>ne, the 5th mantle end member after DMM (depleted MORB mantle), EM1+2 (enriched mantle), and HIMU (high U/Pb) mantle defined by the conversions pseudo-linear arrays of Sr-Nd-Pb.

[2] PHEM = <u>p</u>rimitive <u>he</u>lium <u>m</u>antle defined by He-Sr, He-Nd, and He-Pb isotope arrays.

[3] Note that in this case it is generally accepted to place the radiogenic ^{4}He isotope in the denominator.

Data/results

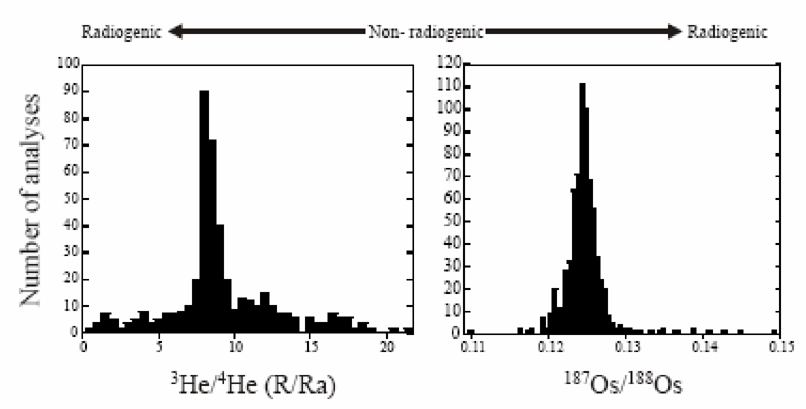
Typical $^3He/^4He$ ratio values found across the world

The highest He ratio ever measured (>50R_A) was at Baffin Island [*Stuart*, 2003]. Typical MORB He isotope ratios are 8±1 R_A, whereas for hotspots ratios are often as high as 24 R_A (e.g. Yellowstone, Hawaii, or Iceland). It is assumed that OIBs are the source for hotspots. For comparison, OIB He ratios are often very low at around 6 R_A but actually vary between 1 R_A and 42 R_A [A. Meibom, 2003]. For continental rocks $R_A << 1$ due the high U + Th concentrations in the rocks. However, when observing He ratios in extraterrestrial bodies, R/R_A can equal as much as 200. This was probably the concentration ratio of helium in the Earth when it just formed. The Earth is however constantly degassing, transporting Helium from the crust and mantle into the atmosphere. In addition, He is a very light element and is continuously being lost into space from the atmosphere. The average residence time of He is 1-2 Myr in the atmosphere.

Graphs/figures/tables

Anderson has demonstrated that the He isotopic signatures from OIBs and unfiltered basalts from oceanic spreading centres with 95% confidence interval are drawn from the same statistical population. See fig. 1

Fig.1



[4]

From Anderson, 2000

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[4] Figure 1. Compiled He isotopic distribution of unfiltered, global spreading ridge data, the vast majority being MORB samples with a few back-arc basin and near-ridge seamount samples included (left) and Os isotope composition of more than 700 mantle-derived detrital Os-rich platinum group element alloys from tectonized peridotite bodies in a variety of tectonic settings along the coast of northern California and southwest Oregon [4] (right). Both distributions display large variability with a nearly Gaussian peak.

Anderson also showed a relation between helium and argon isotopes in MORB and OIB and the effects of degassing and "contamination" with air and older CO_2-rich vesicles in fig. 2

Fig.2 ^{4}He vs. ^{4}He/^{40}Ar* for mantle samples. (Redrawn from Honda and Patterson (1999))

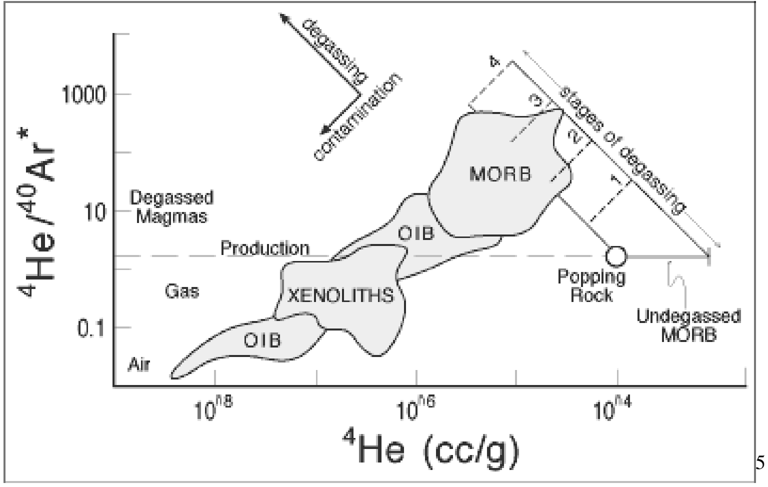
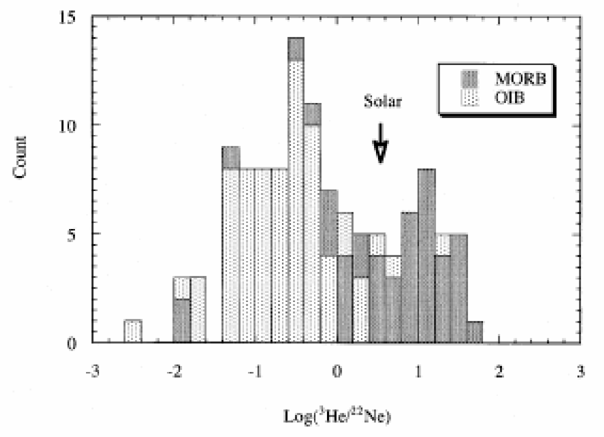

[5]

Fig.3 Histogram of the ^{3}He/^{22}Ne ratio in MORB and OIB.


[6]

From M. Ozima, 1999

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[5] "Popping Rock" (Sarda et al., 1999) is the best approximation we have to a primary magma only slightly affected by degassing. A possible range of undegassed MORB is shown. Such basalts evolve as shown for 1 to 4 stages of degassing. Contamination of degassed magmas by air, seawater, xenoliths and lithospheric vesicles will move the degassed magma toward the lower left of the diagram. Note that MORB contains much more ^{4}He (and ^{3}He) than OIB. OIB appear to be mixtures of MORB, air and xenolith helium.

[6] Ozima et al, discovered that He/Ne and He/Ar are lower in OIB than in MORB, suggesting OIB is less degassed than MORB, as opposed to the general belief that heavy noble gasses are expected to have a greater tendency to degas upon eruption than helium, so He/Ne, He/Ar etc. should be higher, the more degassed a rock is.

Table 1 He fluxes:

	Kilauea (Hawaii)	World ^{3}He from oceanic ridges
^{3}He flux	10 mol per year	± 1000 mol per year
Eruption rate	>0.25 km^3/yr	18km^3/yr

From Anderson, 1998

Discussion

The Standard model

During the 1980s and early 1990s the mantle plume model was still actively and widely supported. The plume model suggests that intraplate volcanism can only be explained by the upwelling of hot material from the core-mantle boundary. In the standard model the mantel is separated into two magma reservoirs. One reservoir is located in the upper mantle and is depleted, degassed, and homogenised. The other reservoir is the lower mantle, which is little or undegassed, containing a higher amount of ^{3}He than the upper mantle. Evidence for this comes mostly from reasoning and the fact that calculations of He isotope ratios and other isotope ratios show that there must be another less depleted, or undegassed reservoir. For example, the inferred mass flux of ^{4}He from the mantle is far lower than that predicted from the decay of U and Th in the whole mantle (O'Nions and Oxburgh, 1983), which suggests the existence of a boundary layer that decouples the flow of He and heat from the lower mantle. Kellogg and Wasserburg have set up a box model in 1990 and calculated the fluxes of helium for hotspots and mid oceanic ridges. They found out that the "efficiency of outgassing at hotspots is high (>0.68) and as a result hotspots dominate the outgassing of ^{3}He derived from the lower mantle" [Kellogg and Wasserburg, 1990]. In addition, as has been noted in the introduction, the MORB He isotope ratios are similar throughout the world at a mean of 8±1 Ra demonstrated by several data processing techniques. On the other hand, measurements at hotspots have shown He isotope ratios around 24Ra up to 50Ra. So it means that these high He ratios must come from another source, rich in ^{3}He, and could only be from a deeper source.

A variation on the standard model has also been set up taking only into account single layer mantle convection. F. Davies reasons that in his model of single layer mantle convection the "helium isotope constraints would be met if the deepest mantle has been less degassed, or if some helium is leaking out of the core" [G. F. Davies, 1990]. Still one would wonder if the whole mantle were indeed convecting, how can it be that over the Earth's lifetime there still would exist an undegassed He reservoir in the lower mantle? The answer can only be that the earth's mantle must be heterogeneous.

Especially in the last 10 years, the standard model is no longer firmly supported due to recent discoveries and recalculations of He isotope ratios measured at various locations. First of all, mass balance calculations show that it predicts an unreasonably high concentration of ^{3}He, relative to other volatiles and incompatible elements in the lower mantle [Anderson, 1989]. It means that, unless there is no or almost no U + Th in the lower mantle, over the Earth's lifetime much ^{4}He has been produced via alpha decay. Therefore, the ^{3}He concentration must be high as well to still overcome the addition of ^{4}He. Calculations made by Kellogg & Wasserburg in a paper presented in 1990 showed that the ^{3}He concentration should be an order of magnitude less than in chondritic meteorites, relative to the refractory elements. However, one would expect it to be several orders of magnitude less, noting that it is a highly volatile element [see figure 11.10 W.M. White]. The higher ^{3}He/^{4}He ratios found at the earth's surface, the more ^{3}He would need to exist in the lower mantle, making the problem bigger.

Secondly, there is good evidence that during the earth's accretion and the impact of a mars-sized body, the earth went through extensive episodes of degassing. Many scientists believe that the earth was once covered with a magma ocean making it unlikely that deep in the Earth light elements are abundant. Many observations agree that the earth's interior is strongly depleted in volatile elements such as Na, K, Cl, CO_2, H_2O, and Rb. Mass balance equations show that 70% of the earth's mantle must be depleted in the volatile and crust-forming elements and concurs with the present amount of Ar in the atmosphere [Anderson, 1989]. Because the mantle above the 670km discontinuity is only 30% of the entire mantle it means that the undepleted helium reservoir would have to reside even deeper in the earth's mantle than below the 670km discontinuity, possibly at the D'' boundary layer.

Thirdly, as figures 2 and 3 show, the observation of helium-3 at higher concentrations in the lower mantle than in the upper mantle cannot be correct if the helium abundances in OIB are lower by a magnitude of 2-3 as compared to MORB helium abundances. Even if there is preferential degassing of heavier noble gasses at OIBs due to their shallow depth of eruption, figure 3 shows that neon is erupted at a lower concentration relative to helium than at MORBs, falsifying the statement.

Fourthly, after extensive data sampling at mid oceanic ridges, it has been discovered that there is considerable variation in the ^{3}He/^{4}He ratio in MORBs. "Young ridges, ridges developed in back-arc settings or by expansion of existing ridge systems, and near axis seamounts tend to have higher and more variable ^{3}He/^{4}He ratios than mature, steady state ridges. Abandoned ridge systems have even lower ^{3}He/^{4}He ratios." [A. Meibom, et al, 2003]. This weakens the argument for mantle plumes, because no longer can it be justified that at MORBs the helium ratio is low and does not vary. A variable helium isotope distribution is not consistent with the standard model, because in the standard model it was thought that the magma source at mid ocean ridges is from a homogenised degassed reservoir and that high and variable He ratios come from an undegassed lower mantle reservoir.

Lastly, it has become a practice that for many hotspots the highest ^{3}He/^{4}He ratio found defines the helium isotope ratio of the hotspot, instead of an average or a median. For example, at Yellowstone or at Hawaii, some high helium ratios have been found in the order of 16 to 35 Ra respectively. However, not far from this sample point, helium ratios close to the MORB helium ratio have been found. Studies at Hawaii conducted by DePaolo et al. (2001) have shown that the Helium isotope ratios in the basalt at the Mauna Loa volcano have been much higher in the past from 18-20 Ra 250,000 years ago to 8-9 Ra presently. Thus, the ratios often exhibit dramatic temporal en spatial variations [Anderson, 1999]. This also means that if an average were taken of the helium isotope ratio at a hotspot, it will not differ much from helium ratios found elsewhere at MORBs or at OIBs. Figure 1 shows that indeed the He isotopic signatures from OIBs and unfiltered basalts from oceanic spreading centres with 95% confidence interval are drawn from the same statistical population [Anderson, 2000]. A possible solution to this problem has been thought of earlier on. White and Duncan (1996) suggested that the hotspot is either not fixed in place or the movement of the oceanic crust over the mantle plume causes the isotopic signatures of magmas to become more 'depleted' as volcanoes evolve. I.e. the mantle plume becomes more and more contaminated with crustal material as time moves on. This, however mainly applies to Hawaii or other oceanic hotspots.

As back up for the standard model, more recently Courtillot et al. (2003) came up with five criteria that determine the presence of a deep source mantle plume. These criteria are: (1) the presence of a linear chain of volcanoes with monotonous age progression, (2) that of a flood basalt at the origin of this track, (3) a large buoyancy flux, (4) consistently high ratios of the three to four isotopes of helium, and (5) a significant low shear wave velocity (V_s) in the underlying mantle. Seven of the world's hotspots adhere to these criteria including Hawaii. Interestingly one of the criteria is the $^3He/^4He$ ratio while currently it is the most debated proof for the existence of mantle plumes. Courtillot et al. go even as far as claiming that the deep mantle plumes are "probably anchored on chemical heterogeneities deposited in the D" layer" [Courtillot, 2003]. Nevertheless, whether the use of the He ratio criteria is justified remains to be seen.

An Alternative model

Even though the standard model is currently heavily under attack, alternative models are still in a preliminary stage. These models describe for example the presence of layering below 670 km depth, or the preservation of heterogeneity in highly viscous regions in the Earth's mantle. They "appear to be able to explain one or more features better than the classical model, but often cause new conflicts with existing geochemical or geophysical observations. In addition, it is not always clear that these new conceptual models are physically realistic" [van Keken, 2003].

Nonetheless, a convincing model concerning the high $^3He/^4He$ ratios at hotspots has quite recently been developed, all indicating that the high helium ratios originate from the upper mantle. However, in this model as well as in many others it must be assumed that the upper mantle is heterogeneous.

This heterogeneity helps helium, a highly volatile gas, to remain in place in the upper mantle. Helium is transferred via two possible methods, in the deeper part of the mantle it is a dissolved gas in magma. At shallower depth, however, it is exsolved along with CO_2, which is its main carrier phase. Naturally, not all helium can escape. Part of it is trapped in crystals or in inclusions in *restite*[7] together with a CO_2-rich fluid. Because of strong evidence against the notion that there exists elevated ^3He concentrations in the mantle, regardless whether it should be in the lower or in the upper mantle, some scientists now believe that somehow the ^4He component must be at a lower than normal concentration in order to get elevated helium ratios.

In the model proposed, it has been suggested that the storage of old helium resides in a low time-integrated U+Th host rock in the upper mantle. Several pieces of evidence support this theory. Ricard et al. (2001, 2002) came up with quantitative support for this non-primitive source of high $^3He/^4He$ is provided by a number of models. Other calculations show that because of the residence time of recycled material (1 to 1.5 Byr), U+Th depletion of the protolith is not required if this is mixed with a small volume of ^3He rich material (Ballentine et al., 2002). The latter calculations are consistent with radioelement and noble gas concentrations inferred from the Iceland plume (e.g., Hilton et al., 2000). In addition, high helium ratios have been observed in Samoan xenoliths known to come from the upper mantle. Mining of diamonds from pipes also surprisingly contain high $^3He/^4He$ ratios. Lastly, high helium ratios have been observed at Yellowstone, a hotspot now agreed upon to have a magmatic system limited to the lithosphere [Christiansen et al., 2002].

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[7] The residual refractory residue of basalt extraction. Due to the absence of garnet, it is less dense than basalt. It is olivine rich and resides below the crust, above the fertile mantle.

A similar discovery that could explain the higher than normal He ratios was made by Natland (2002). In experimental work, he showed that ^{3}He can be captured in individual olivine crystals. The inclusions that form during magmatic processes for olivine growth of ascending magma at mid ocean ridges take in some He together with CO_2 and effectively trap helium in the bubbles. Olivine itself contains no U+Th and any alpha particles (^{4}He) that encounter olivine are unable to penetrate the olivine crystals due to insufficient energy. Thus imagining that some helium was captured in olivine crystals when the earth was still young, the preserved high He ratio remains unchanged. Experiments also showed that it is almost impossible for ^{3}He to escape, not due to a concentration gradient that inevitably exists, but due to the differences in the chemical potential. "High partition coefficients can block diffusion even in the presence of large concentration gradients" [Anderson et al., 2003]. He, despite being highly volatile, proves to be essentially insoluble in olivine itself. Thus, it will tend to remain inside the inclusion in the olivine crystal.

The alternative model is strongly supported by this recent discovery of He being trapped inside olivine crystals. It, being widely supported by Anderson, Meibom, Stuart, Foulger, and others, concludes that the high ^{3}He/^{4}He ratios are found in the cumulate olivine-gabbroic layer belonging to the lowermost crust. This layer contains densely packed cumulates that have compacted and squeezed out the interstitial melt, thereby expelling essentially all the U+Th. Assuming that when this oceanic crust is not subducted to depths as far as the lower mantle, but remains in the upper mantle, then upon melting eventually high helium ratios are expelled to the atmosphere. The high He ratio of course depends on several factors such as the age and amount of the olivine-rich layer, how much He was trapped, and the amount of ^{4}He produced in the surrounding rock. Again, as figure 1 shows, stochastic sampling of this source predicts Gaussian distributions of the ^{3}He/^{4}He isotope ratios similar to MORB. It also demonstrates that in the upper mantle there is mixing going on between different proportions of ancient radiogenic and unradiogenic domains. The extent to which the helium isotope ratio will vary depends on the degrees of partial melting and on the volume of magma involved (see fig. 2). For MORB magmas the volume is large and the degree of partial melting high, as opposed to OIBs. This explains the apparent constant He ratios at MORBs and the near Gaussian distribution. This evidence would seem to prove that indeed the high He ratios come from the upper mantle.

As a side note, Anderson presented in 1998 some data (see table 1) on ^{3}He fluxes from the Hawaiian hotspot and the world ridges. The ^{3}He output from Kilauea is about 1% compared to what is exhaled at the ocean ridges. In addition, the magma eruption rates from Kilauea is more than 1% of the of the global mid-ocean ridge production of 18 km^3/yr. This concludes how trivial the amount of ^{3}He output from hotspots is compared to degassing from oceanic ridges and island arcs. "Paradoxically, there is more ^{3}He outgassing at island arcs than at all hotspots combined" [Anderson, 1989].

This alternative model, nevertheless, cannot account for all hotspots, just as the mantle plume theory no longer accounts for all the hotspots in the world. The first question that would arise is of course, what if subduction of the oceanic crust can go into the lower mantle as has been suggested for seven hotspots by Courtillot et al? Is this then not the source for high ^{3}He/^{4}He ratios at hotspots of deep origin and is this then not the proof for the existence of mantle plumes, not from an undegassed, primitive mantle, but from subducted oceanic crust? Moreover, as long as there is no concrete proof against the existence of ^{3}He at the D" layer, even lower ^{3}He concentrations can travel via a mantle plume to the Earth's surface and on its way mix with this cumulate olivine-gabbroic layer becoming enriched in ^{3}He yielding a high ^{3}He/^{4}He ratio. Lastly, when observing hotspots such as Yellowstone, one could raise the question if the mantle plume is simply ceasing to exist but still contributes high He ratios and a high heat flux to the surface. However, "an entire plume head gone missing does cause concern" [Sheth, 2003].

Conclusion

Helium, one of the few geochemical tracers, showed at first strongly that magma at hotspots must come from an undegassed, primitive reservoir thought to reside in the lower mantle. Thirteen years later, or thereabouts, it seems that the ^{3}He/^{4}He ratio is no longer confined to the notion that it must come from the lower mantle but can equally well come from the upper mantle.

The standard model has proven to contain several problems such as calculations showing that the helium isotopic signatures of OIBs, that can have a ^{3}He/^{4}He ratio up to 42Ra, is actually quite identical to MORB helium isotopic signatures. Also the standard model does not clearly explain how come ^{3}He, a light and very volatile element, that cannot be produced (in any significant quantities) can exist in a greater concentration in the lower mantle when it is universally accepted that the Earth was once molten and went through extensive episodes of degassing. Most other problems with the standard model come from recalculations of helium ratio measurements for example at hotspots, at mid ocean ridges, and at island arcs. ^{3}He/^{4}He ratios indeed do vary at mid ocean ridges with age. Additionally, critics believe that it is unjust to take the highest helium ratio measurement at a hotspot and compare it to mean He ratio measurements taken at other locations. Lastly, one would wonder how it is possible that at hotspots, measurements of helium at one location give a high ratio and not far away a much lower ratio close to what is measured at mid oceanic ridges. How can a mantle plume, which supposedly brings high ^{3}He/^{4}He ratios to the atmosphere from the core-mantle boundary, explain this spatial variation? In addition, there also clearly is evidence found for temporal variation, for example at Hawaii. A stable, long-lived mantle plume should not yield a drastic change in ^{3}He/^{4}He ratios over time.

However, the alternative model provides no hard proof against the possibility of higher ^{3}He/^{4}He ratios to exist at the core-mantle boundary when for example assuming that the U+Th concentration is low at the D" boundary. The alterative model was set up to provide and alternative source for high helium ratios, simply because the standard model proves to be flawed in several aspects. However, the alternative model assumes that the oceanic subducted slabs do not enter the lower mantle but serve as "fuel" for hotspots in the upper mantle, thereby eliminating the need for mantle plumes. If the assumption is proved wrong, the alternative model fails to completely explain the high ^{3}He/^{4}He ratio at hotspots just the same.

Nevertheless, the extent to which this helium ratio can be used as a geochemical tracer to localise the source and confirm the existence of mantle plumes at hotspots has become little. This can be justified by the fact that since the mid nineties no more models have been set up concerning high helium ratios from mantle plumes at hotspots. However, the reason why the mantle plume model still persists today is because it is not only based on evidence from the field of geochemistry but also from seismological evidence as well as other evidence. The model is very customisable and can well explain a variety of phenomenon seen at hotspots. The current alternative models, based on plate tectonics, all explain well one feature of hotspots, but cannot explain another. No doubt, however, that if indeed clear proof is given that mantle plumes from the core-mantle boundary do not exist, the alternative model will prevail.

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