The Statistics and Distribution of Helium in the Mantle

by

Don L. Anderson

California Institute of Technology

Seismological Laboratory 252-21

Pasadena, CA 91125 U.S.A.

626.395.6901

FAX: 626.564.0715

E-mail: dla @gps.caltech.edu

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Abstract

An unbiased estimate of the $^3He/^4He$ ratio (R) along the Earth's spreading ridge system is

$$9.14 \pm 3.59 \text{ Ra } (n = 503)$$

where Ra is the atmospheric ratio (1.38×10^{-6}).

By arbitrarily excluding all values with $R > 11$ Ra and from ocean depths less than 2500 meters, I obtain

$$7.91 \pm 1.50 \text{ Ra } (n = 212)$$

which is close to previous 'filtered' estimates based on the hypothesis that the excluded values have been influenced by plumes. These are biased estimates.

Based on unbiased statistics many of the so-called high-^3He hotspot regions have isotopic ratios well within the MORB range, and all have absolute ^3He concentrations much less than MORB. The high variance of some oceanic island data compared to MORB reflects, in part, the difference between a small sample and a large sample, and magma chamber processes.

Values of 11-15 Ra are commonly attributed to deep mantle plumes and "indicative of lower mantle involvement", but these values are within 2σ of the mean and are not exceptional. Much higher values combined with low absolute helium concentrations are commonly associated with the onset of rifting, or volcanism, and may reflect a shallow, or lithospheric, low $^{238}U/^3He$ (LONU) source. The temporal progression to average MORB-like values suggests that the bulk of the magmas at spreading ridges and large oceanic constructs come from below the LONU level. The termination of spreading is associated with low ratios, 6-7 Ra, similar to values associated with the HIMU mantle component and some oceanic islands.

Background

Helium-3, like most of the isotopes in Earth, was brought in during accretion, some 4.5 billion years ago, or, along with other volatiles, as a late-veneer, mostly prior to stabilization of the crust. Some amounts of ^{3}He are still being brought in as interplanetary dust particles (IDP) which can dominate the helium budget of deep sea sediments. Some of the highest ^{3}He concentrations to be found in Earth are in abyssal sediments. Because of its pedigree ^{3}He is referred to as a ‘primordial isotope’. Since the termination of accretion, and the late-veneering process, the amount of ^{3}He in the mantle has been essentially constant, except for that fraction that is vented to the surface and lost to outer space. Most ^{3}He atoms are vented from the mantle at midocean ridges and island arc volcanoes. A small fraction is lost through continents and at the so-called ‘hotspot’ or ‘midplate’ volcanoes. A small amount is made by cosmogenic and nucleogenic processes.

The number of ^{3}He atoms brought in currently by IDP is about the same as the number expelled from the interior at 'hotspots' (Anderson, 1993). However, neither the influx nor the volcanic flux can be considered constant. Anderson (1993) argued that currently degassing ^{3}He at oceanic islands probably entered the mantle at least 10^{9} years ago. Conditions between then and 4 Ga were more favorable for helium retention than during the bulk of the accretion process. The issue of when and how the noble gases entered the Earth, however, is different from the issue of where and how the domains of different ^{238}U/^{3}He (ν) formed. I argue in this paper and in Anderson (1998a, b) that the LONU reservoir is more likely to be low [He] and shallow, rather than high [He] and deep in the convecting mantle.

Since ^{3}He is a ‘primordial element’ and is an easily lost gas, it is often assumed that it must come from ‘primordial mantle’, mantle that has not been subjected to melting or degassing.

The assumption here is that once ^{3}He leaves its primordial parent rock, it is rapidly transferred to the atmosphere, i.e. there is no intermantle transfer of He-bearing fluids from one rock to another. The logical mistake here is confusing a *Primordial Component* with a *Primordial Reservoir*.

Most of the ^{3}He atoms that can be accounted for are in midocean ridge basalts, and most of the gaseous ^{3}He escapes at midocean ridges and island arcs (Sano and Williams, 1996). Nevertheless, it is a common assumption that the bulk of ^{3}He in Earth is stored in primordial undegassed lower mantle (Porcelli and Wasserburg, 1995) although the basalts presumably from this reservoir have very low ^{3}He concentrations compared to MORB which is commonly thought of as coming from a degassed reservoir.

Helium-4 is a radioactive decay product of U and Th, and therefore builds up in the crust and mantle over time. The ^{3}He/^{4}He ratio of the crust and atmosphere is very low because the crust has high abundances of U and Th. More than 50% of these elements are in the crust (Anderson, 1989) and degassing of crustal helium is responsible for the low ^{3}He/^{4}He ratios of the atmosphere and seawater (1.38×10^{-6} is the atmospheric ratio, Ra). Mantle gases, and gases in mantle-derived basalts have higher ratios, R, generally falling in the range of 5 to 20 Ra (e.g., Farley and Neroda, 1998). This is due to the low ^{238}U + ^{235}Th of the mantle compared to the crust.

The ^{3}He/^{4}He ratio [R] of a closed system (no import or export of helium atoms) depends on the time integrated ^{238}U/^{3}He ratio, for a given U/Th ratio. This ratio is called ν, or NU. A similar ratio, ^{238}U/^{204}Pb, called μ or MU, is important in discussions of Pb-isotopes in mantle magmas. Some oceanic basalts have high MU (HIMU) ratios, attributed to recycling of ancient oceanic crust. The corresponding parts of the lithosphere, having been depleted in **U** (= U + Th) to form the crust are LOMU, and being depleted in other large-ion incompatible (LIL) elements, such as Rb and Sm, do not contribute much to basalt chemistry, even if it is recycled along with its overlying crust.

Basalts which have low time integrated **U**/^{3}He ratios (LONU), compared to the crust, will have higher R than the crust, and atmosphere, the most common values lying between 7 and 9 Ra. Various reservoirs (sources of gas and magma) in the mantle can have different R if they differ in age, NU, **U** concentrations or ^{3}He concentrations. The rare basalts which have R much higher than 'average' MORB are widely assumed in the geochemical literature to have 'excess-^{3}He' and therefore to come from a primordial undegassed reservoir, isolated from the convecting upper mantle. The alternatives, low **U** or different age, are generally not discussed although 'high R' basalts are low in ^{3}He (low [^{3}He]).

Helium is transferred around in the shallow mantle as a dissolved gas in magma. At shallower depth He exsolves, along with CO_2, its main carrier phase, and part is trapped in crystals or retained as CO_2-rich fluid-filled inclusions in *restite*, the residual refractory residue of basalt extraction. Restite is less dense than the original fertile (capable of producing basalt) mantle because the basaltic component at depth (eclogite) contains garnet, the densest upper mantle mineral. Restite is olivine-rich and buoyant and therefore collects in the shallow mantle, below the crust and above fertile mantle. It is geochemically barren except for the compatible elements (such as Os) and trapped fluid-filled inclusions. The restite layer, when cold and strong, is called the lithosphere, the primary structural component of the plate. Old lithosphere, particularly at fracture zones, faults and sutures can become metasomatized, due to transiting fluids of various sorts. Such metasomatized regions of the lithosphere are preferentially sampled by magmas since these regions are preferred conduits. The bulk of the restite in the shallow mantle, particularly the intact parts of the lithosphere, may retain ancient isotopic signatures and retain its low-**U** and low-LIL character.

Various components have been identified in ocean island basalts, and along some ridge segments. These have been attributed to various parts of the recycled slab; EM1 and EM2 (pelagic and continental sediments) and HIMU (oceanic crust). Occasionally a component is attributed to ‘continental lithosphere’, but the oceanic restite layer is seldom considered in mantle geochemistry. In addition to continental and oceanic lithosphere (the latter usually being assumed to be less than 200 million years old (200 Ma)), there are plateaus, swells and shallow parts of the ocean basins which may have ancient restite roots. A global restite layer, possibly about 100 km thick, is the result of accretional differentiation and billions of years of melt extraction. It is a buoyant isolated reservoir and is probably thickest under ancient cratons and some oceanic plateaus. When it is colder than some 600°C it is strong and is the "lithosphere". This part of the outer shell, plus the overlying crust, probably constitute the "slab" that recycles into the mantle. The warmer, deeper, more buoyant parts of the restite shell may remain in the shallow mantle, overlying 'fertile' mantle. This 'floating reservoir' is seldom considered in geochemical box models. In fact, it may be important only for the noble elements and the more compatible elements since, by definition, it has had basalts and LIL extracted.

The spatial and temporal relationships of enriched and depleted magmas, and of helium isotopic ratios, suggest that the shallow mantle is an important reservoir. Whether the inhomogeneities are arranged in layers (crust, lithosphere, restite shell, perisphere, depleted reservoir) or plums (plum pudding, marble cake) there will be similar temporal or spatial variations, and variations depending on when and how the samples are obtained. "Midplate" or "hotspot" volcanism is better termed "initial" or "transient" or "small scale" magmatism, this better reflecting the temporal and tectonic contexts. The 'mantle wedge' above subduction zones and metasomatized continental lithosphere (CL) are two of the more obviously enriched shallow reservoirs.

Introduction

It is usually assumed that midocean ridge basalts are derived from a homogeneous, well-mixed depleted degassed reservoir, often equated with the ‘convecting upper mantle’. Chemical heterogeneity found along the global midocean ridge system is attributed to:

1. injection of enriched or 'primordial' material from lower mantle plumes
2. incorporation of delaminated continental lithosphere that somehow arrives at the ridge
3. the presence of dispersed heterogeneities in a continually remixed convecting mantle
4. introduction of subducted and recycled components
5. contamination of depleted MORB by shallow layers upon eruption, or in magma chambers.

If the MORB mantle is homogeneous at all scales then heterogeneities must be introduced from outside, as in the plume hypothesis. If the shallow mantle is heterogeneous then the chemistry of magmas will reflect the sampling process, and history of sampling. There are many continental fragments (Seychelles, Lord Howe Rise, Jan Mayen, Broken Ridge…) trapped in the ocean basins, some of which are covered with basalt. These oceanic plateaus are overlooked potential (floating) reservoirs or sources of "contamination".

The narrow range in the ^{3}He/^{4}He ratio in MORB is often taken as evidence for the homogeneity of the MORB source and evidence that it is a convecting well-stirred reservoir. However, the actual statistics of the ^{3}He/^{4}He distribution in the upper mantle are unknown since values outside of a given range are commonly deleted as being “contaminated by plumes” or recycled material. The MORB reservoir itself need not be homogeneous since the large degrees of melting, the large sampling volumes, and magma chamber processes, serve to blend various components in more effective ways than available to xenoliths, melt inclusions, seamounts and oceanic islands. The narrow range of isotopic and trace element characteristics of MORB, compared to other magmas, may simply reflect the sampling process rather than a uniquely well-mixed shallow mantle reservoir.

Anderson (1989) presented a model in which all mantle magmas, including MORB, are blends of components. Even the most depleted MORB is a hybrid, not a pure component. It simply has less of the enriched components (EM) than some smaller scale samples, such as seamounts and islands. Niu et al. (1999) and Niu and Batiza (1997) have recently found that near-ridge seamounts exhibit a range of compositions, from more depleted to more enriched than MORB, but the average composition is N-MORB (Normal-Midocean Ridge Basalts). More of the enriched component gives E-MORB. Even axial basalts have OIB-like components. This gives strong support to the idea that the upper mantle is heterogeneous and that magma compositions depend on how the source is sampled.

The theory of statistical sampling tells us that pooled samples from a large volume of sample space will be relatively uniform and reproducible while small individual samples will tend to be more diverse. Repeated small scale sampling gives a larger variance than repeated large scale sampling, but the means may be similar.

Islands and seamounts sample a smaller volume of the mantle than MORB and, accordingly, they should and do display a large diversity in chemistry. The question is, can MORB and island basalts be different kinds of samples from the same heterogeneous reservoir? The fact that near-ridge seamounts provide samples that are both more enriched and more depleted than axial MORB, and that there are approximately as many low-^{3}He/^{4}He oceanic islands as high-^{3}He/^{4}He islands suggests that sampling statistics may be responsible for the diversity of magmas and for the statistics of helium distributions.

Statistical treatment of all samples obtained on or near ridges is the best way to determine the average composition of the shallow mantle. The statistics of ridge geochemistry may approximate a Gaussian curve, while smaller subsets (e.g. seamounts, EPR from 17-22°S, North Atlantic Ridge 52-70°N, ocean-island basalts, etc.) will approximate a t-distribution, with a similar mean but much larger variance, and more extreme values. If there is a temporal evolution, or a stratigraphy, from high R to low R, then a given ridge segment, rift or island may yield a one-sided distribution, reflecting the stage of the volcanism. To fully define the distribution, including the high and low-R tails, requires sampling in all tectonic environments and at various stages of rifting.

The first order of business is to compile ridge data and then determine unbiased means and standard deviations. When this is done the various hypotheses that have been proposed for different regions can be tested. It is important not to process the data in advance, with a particular hypothesis in mind. Currently we do not know the ‘expected value’ or what is a ‘significantly’ different value when we discuss helium anomalies.

^{3}He/^{4}He ratios of 11 times the atmospheric ratio (Ra) or greater are now routinely referred to as ‘plume’ components or evidence for ‘lower mantle’ involvement (e.g., Poreda et al., 1993; Niedermann et al., 1997). Such values are stated to be “significantly higher than the MORB average” which implies that an unbiased statistical description of MORB samples is available. Currently available compilations, for helium, have discarded values higher than 11 Ra (or 9 Ra, or 9.5 Ra, depending on the author) or “having other evidence of N-MORB (sic.; non-

MORB?)… characteristics" (Hilton et al., 1993). There is thus a large degree of circular reasoning in many recent papers where a "plume" or "lower mantle" component is invoked entirely or mainly on the basis of a few high R (and very low [^{3}He]) samples. Standard methods of statistical inference and hypothesis testing can be applied to the helium database but not to a hypothesis-dependent 'filtered' database.

Filtering Data

Previous estimates of helium statistics along the oceanic ridge system are 'filtered' with a particular hypothesis in mind. For example:

> "Samples of ^{3}He/^{4}He greater than 9.5 Ra were not used as they are considered to be influenced by primitive plumes from the lower mantle."
>
> (Sarda et al., 1999)

> "…MORB sample data were filtered in an attempt to include only samples uninfluenced by plumes or hotspots…". Samples from less than 2500 meters depth or having "other non-MORB…characteristics"…were removed from the dataset.
>
> (Hilton et al., 1993)

Hilton et al. (1993) also discarded values higher than 11 Ra in compiling their backarc basin statistics obtaining (8.18 ± 0.73), thinking that Lau Basin basalts are contaminated by the "Samoan plume" (on the other side of the Tonga-Fiji slab), although samples geographically closer to Samoa, with 'normal R' are retained in the compilation. Subsequently, other backarc basins have been found to include high R samples (MacPherson et al., 1998). Backarc basin spreading centers are isolated from the deep mantle by the underlying slab and are ideal locations for sampling the shallow mantle.

Fisher (1986) defined 8 ± 2 Ra as the range for ‘normal MORB’, and this provided his criteria for filtering data. Based on published compilations prior to 1976 and unpublished data (abstracts, theses, personal communications) up to 1984, the range typical for MORB was given as 7.0 - 9.0 Ra by Poreda et al. (1993). The value 8 ± 1 Ra has generally been used since that time. Subsequently, values up to 11 Ra found along ridges have been treated as “definitive evidence” for a hotspot or plume signature. Apparently, authors of recent papers are not aware of the strong *à priori* filtering that has been applied to the MORB dataset, or have forgotten.

Values of 11 Ra or greater are ascribed to the involvement of deep mantle plumes implying that there is very low or zero probability of such values being available in the MORB reservoir or the result of shallow contamination. For example;

> “The definitive evidence for the presence of a hotspot signature on the East Pacific Rise was the discovery of ^{3}He/^{4}He ratios in basalts that were greater than those of MORB (R/Ra > 8), with values ranging up to 11 Ra.”
>
> (Poreda et al., 1993).

Midocean ridges induce upwellings of large volumes of the mantle and generate large degrees of melting. They also process and blend magmas obtained over a large depth interval. Most ridges are mature and no longer sample (at least, without blending) the shallow parts of the mantle they may have sampled when they were younger or their ocean narrower. The north Atlantic, the Red Sea, the East African Rift, ends of propagating ridges, microplates and backarc basin ridges are places where new ridges may be sampling the shallow mantle in a different way than mature ridges.

The places to search for extremes in shallow mantle helium ratios and concentrations are at slow spreading ridges, regions of fracture zones, seamounts, low degree melts, initial and final melts, and xenoliths. Dense sampling along ridges may give a more representative range of helium isotopic ratios than widely spaced samples. "Spikes" of anomalous chemistry, however, are often attributed to "plumelets" or lower mantle components rather than to intrinsic variability. The south Atlantic near the Bouvet triple junction is a region of slow spreading, numerous fracture zones and unstable plate boundaries. One expects a wide range of ^{3}He/^{4}He ratios in such regions. Some of the lowest ratios in the south Atlantic are from very shallow samples, and some of the highest ratios are among the deepest samples (Kurz et al., 1998). Therefore, the criteria used by previous authors to “filter” samples from the north Atlantic does not apply. Since high ^{3}He/^{4}He ratios occur at various elevations and depths and since they are commonly interspersed with 'normal' values on oceanic islands and since the samples are often identical to normal MORB in other respects, there is no unbiased procedure for eliminating them from the dataset. One cannot, and should not, assume that extreme values in complex environments must be imported from the deep mantle. One should also not compare extreme values from one tectonic environment to average values in another.

Preliminaries

The ^{3}He/^{4}He ratio of a mantle source region depends on many factors, most of which are expected to display a broad, perhaps Gaussian, distribution:

1. U/He ratio

2. U/Th ratio
3. age
4. introduced components
5. prior history

One expects, therefore, that basalts derived directly from any part of the mantle will have a broad distribution of $^3He/^4He$ ratios since it is unlikely that any of the above parameters, much less their integrated effects, will be single valued.

The high $^3He/^4He$ tail of the distribution is likely to be dominated by low $^{238}U/^3He$ samples and therefore will change little with time. The low $^3He/^4He$ part of the distribution may reflect a higher $^{238}U/^3He$ environment and will grow as radiogenic ^4He is added to the system. Therefore, the mean will shift to lower $^3He/^4He$, with time, and the distribution will become skewed, with a long high R tail. In fact, the R distribution of oceanic samples, both ridge and island, has the general appearance of a log-normal distribution and has more high R members than a normal distribution (Farley and Neroda, 1998). The high R members of the global $^3He/^4He$ ratio histogram are commonly attributed to a deep mantle, high-^3He plume. However, the evidence is that high-R samples are low in ^3He and very low in ^4He, implying a low $^{238}U/^3He$ LONU source (Anderson, 1998a, b). High $^3He/^4He$, low [He] probably has more temporal, or survival, implications than implications about great depth or 'primordial' mantle.

It should be noted that the refractory residual left after removal of basalt (restite) is buoyant with respect to fertile mantle. It will also be strong and high-viscosity because of the removal of water (Hirth and Kohlstedt, 1996). It serves as a carapace over fertile, more volatile-rich mantle and may collect the gases expelled by rising magmas as they pass through the saturation level of CO_2. Helium can also be partitioned into restite and olivine-rich cumulates even if the crystal-melt partition coefficient is low. The important issue regarding the $^{238}U/^{3}He$ ratio (NU) of the lithosphere is the relative partitioning of U, Th, CO_2 and He between crystal, melt and gas, and the nature of the metasomatic fluids (silicate melts, carbonatites or vapor). Buoyant restite is an isolated reservoir that can locally preserve high $^{3}He/^{4}He$ ratios if it is LONU. Subsequent magmas can be influenced by passing through the lithosphere, particularly for helium and osmium isotopes, and perhaps lead and oxygen isotopes. On the other hand, LIL contamination is more likely to occur when the magma interacts with crust.

Countering the trend toward heterogeneity in shallow reservoirs is magma mixing, magma chamber processing and prior removal of inhomogeneities. The sampling process, large vs. small samples, can yield products (samples or sub-populations) from the same reservoir (population), with different apparent variability. Not to be overlooked is the *à priori* processing of the data such as discarding “anomalous” values, resulting in an artificially narrow distribution which can be “puzzling” or, statistically, “too good to be true.”

If magmas are blends of various components the $^{3}He/^{4}He$ ratio of the blend will be dominated by the high ^{4}He components, such as relatively undegassed MORB. If there are solubility arguments for a peak in absolute He concentrations, [He], at some particular value, then this component will dominate the ratio of any blend. If the processes of melt extraction involve degassing at relatively shallow depth, then the degassed magmas and the ultimate repository of the gases (fluid-filled inclusions, cumulates, lithosphere) will have different $^{238}U/^{3}He$, He/Ar and He/Ne ratios and, in time, have quite different $^{3}He/^{4}He$ ratios. Recycled crust will have different ratios than recycled depleted lithosphere. HIMU may be complementary to LONU.

It is now clear that the MORB reservoir is inhomogeneous and contains both very enriched and very depleted components, which are blended in the processes of ridge sampling and magma chamber evolution (Anderson, 1989; Niu et al., 1999). The nature of the heterogeneity only becomes clear with small scale sampling along the ridge and by studying xenoliths, melt inclusions, seamounts and fracture zones. It is still commonly assumed, however, that the MORB-source is intrinsically homogeneous (well-stirred "convecting" mantle) and that heterogeneities are all imported from near-by (or far-away) hotspots, or deep mantle plumes, or delaminated continental lithosphere. This perception of "remarkable" uniformity of the upper mantle (Niedermann et al., 1997) is mainly based on the narrow distribution of helium isotopes (± 10% spread). Some incompatible element show much larger variations, i.e., 50-100% variation (Ba, Rb, Cs, Th, Nb, U, Ta), and ~20% variation (K, La, Ce, Pb, Sr, Nd) (Niu and Batiza, 1997). Compatible elements (HREE, Li, Sc) tend to show variations of order 10%. Even major element ratios (e.g. CaO/Al_2O_3) show scatter of 50% in ridge-derived basalts. If the $^3He/^4He$ ratio of spreading ridge samples is as narrow as perceived in the current literature, then this would indeed be an anomalous, even remarkable, situation. I will show that an unbiased estimate of the near-ridge mantle has a standard deviation of about three times the commonly assumed value, making the $^3He/^4He$ variation consistent with other measures of mantle heterogeneity.

Statistics

Unbiased statistics for the distribution of $^3He/^4He$ ratios along the global spreading ridge system are not available. The mean and standard deviation are usually quoted as 8 ± 1 times the atmospheric ratio, Ra. However, this estimate is based on a much smaller dataset than is now available and is also hypothesis-dependent, the data having been 'corrected' for ‘plume contamination’. The techniques used for this ‘correction’ are arbitrary and involve discarding all values greater than some upper cut-off, ranging from 9.5 to 11 Ra, or discarding all values from ocean depths less than some cut-off such as 2500 meters. These criteria were based on a small sample from the north Atlantic and were for the purpose of eliminating samples 'too close' to Iceland. Some of the discarded values are MORB-like in all other trace-element and isotopic respects.

Subsequently, samples have been found along perfectly normal stretches of the southern hemisphere ridges which have values of 11 Ra or more. In the south Atlantic and near Loihi, some of the deepest samples have the highest R and, in many places, very shallow, and even emerged, samples have MORB-like values.

I have assembled a large fraction of the available data along the world’s spreading systems including new ridges, near-ridge seamounts, the north and south Atlantics, East Pacific Rise (EPR), Chile Rises, Indian Ocean ridges, the Azores, Galápagos, Easter, Shona and Bouvet segments, microplates and backarc basins. This was all analyzed together, to yield the Grand Average, and then in subsets. In contrast to previous studies no datum was discarded because it was outside 'the MORB range', or from too shallow, or had a value too high or ‘was influenced by plumes’. The statistics is only biased by the choices of sampling areas and techniques made by individual investigators.

The results are shown in Figure 1. The black histogram excludes shallow samples, and the white histogram shows all the spreading ridge data. There is no apparent difference between the complete dataset and the data 'filtered' by depth.

Justification for Not Throwing Away Data

High R basalts are found in backarc basins, at triple junctions, fracture zones, seamounts, and near microplates and propagating ridges. These are usually attributed to 'hotspot influence' but they may also represent different modes of sampling normal upper mantle. Low R basalts are also found in these places. Steady-state ridges, with shallow magma chambers, may provide a very filtered and averaged version of mantle heterogeneity.

Backarc basins are generally young, have unstable reorganizing ridges, and are cut off by slabs from the lower mantle. They provide a different sampling of the shallow mantle than steady-state ridges. Triple-junctions often have a complex fracture system which also may provide a different kind of window into the mantle. Near-ridge seamounts may provide a more representative view of heterogeneity than ridge axes. Abandoned ridges and new ridges may provide components that are overwhelmed or diluted at normal ridges. Microplates and propagating ridges certainly utilize different sampling techniques than steady-state ridges.

There is no *à priori*, hypothesis-independent reason for discarding any of this near-ridge data. Often there is no reason other than finding some samples at these locations with R > 11 Ra for invoking a plume or lower mantle component.

Measures of Helium Chemistry

In addition to *averages* and *standard deviations* of various subsets of data, I also utilize other measures.

The *median* is often a more robust measure of the 'representative' value of a population than the average, and this is true for the helium data. The so-called 'high-^{3}He' hotspot regions generally have median R values close to MORB. Unfortunately, often only the highest R values are discussed or plotted (e.g., Marty et al., 1996).

This is the inverse of the way the MORB dataset is treated. Published averages for MORB have had the high R samples removed. Many 'high-^{3}He' hotspots have means and medians within the MORB range, but only the high R samples are compared to the 'MORB average'. When the highest R samples in, say, Ethiopia or Easter or the Lau Basin, are compared with the filtered MORB average, it is commonly concluded that a 'lower mantle' component is present. This is the statistical fallacy of comparing *maximum values* with *means* to conclude that two populations differ. This error is compounded by 'filtering' the data prior to the comparison.

There are often orders of magnitude differences between the absolute helium concentrations, [He], in samples from a given area or in a single investigation. Although samples can degas and measured [He] may not be representative of the magma at depth (or the source), there is increasing use of [He] in discussions of helium distributions (Honda and Patterson, 1999; Ozima, 1994). If the upper mantle is heterogeneous and is sampled by large degree melts, or if magmas are blended in magma chambers, then the high [He] components will dominate. In addition to computing the averages and medians, we also calculate the *[He]-weighted means*, given as, e.g. {8.50}. These means, of course, will be dominated by the highest [He] samples, just as is the case in sampling the mantle or blending in magma chambers. If the shallow mantle is heterogeneous, a normal spreading ridge, with a shallow magma chamber, will yield R values that are dominated by the highest [He] samples. To get a true description of upper mantle heterogeneity one must include samples from fracture zones, seamounts and xenoliths and use dense profiles, without discarding values that fall outside the axial range.

The various statistical measures are useful since the noble-gas literature is dominated by comparisons of OIB maximum values with MORB mean values. This is not a statistically valid procedure, even if the MORB dataset were not 'filtered' by discarding all the high R values.

Results [Table 1]

The Grand Average near-ridge mantle result is

9.14 ± 3.59 Ra (n = 503).

The $\pm 1\sigma$ range is from 5.5 to 12.7 Ra, and the $\pm 2\sigma$ range is 1.9 to 16.3 Ra.

Slightly different datasets yield 9.06 ± 3.26 Ra (n = 456) and 9.23 ± 3.35 Ra (n = 457). Alternate values are given in some cases to test the robustness of the conclusions to changes in the dataset. Data selection is unbiased, but arbitrary decisions have to be made about how to deal with repeat measurements, samples from the same dredge haul, "oversampled" areas, and suspected air-contamination. Some of the datasets differ simply because new data became available while the manuscript was being prepared.

The $\pm 1\sigma$ range captures all of the samples from Kerguelen, Prince Edward, Jan Mayen, Madeira, Canary Islands, St. Helena, Tristan, Gough, Haleakala, Hualalai, most of Guadalupe, Rocard, Teahitia, Mehetia, Gambiers, Pitcairn, Rurutu, Tubuai, and MacDonald even though most of these regions are not in the spreading center datasets used to determine the statistics. The $\pm 2\sigma$ level captures, in addition, Rapa, Savai'i, Mas Afuera, Niihan and Réunion (Farley and Neroda, 1998). These are all considered 'hotspots', 'plumes' or 'samples of the lower mantle'. The younger Mauna Loa and Mauna Kea samples are also in the MORB range.

If Iceland, Kolbeinsey Ridge, Reykjanes Ridge, Red Sea and Ethiopian basalts are considered as transient and shallow products of a new or narrow ocean, or unstable ridges, then high values of R elsewhere may also sample the shallow mantle.

If Ethiopia, Iceland, the far north Atlantic (new ridges) data are removed from the spreading ridge dataset (arbitrarily), the result is

$$R = 8.93 \pm 2.85 \text{ Ra } (n = 395)$$

For comparison the Pacific dataset yields

$$R = 9.20 \pm 3.40 \text{ Ra } (n = 210), \text{ or}$$

$$R = 8.84 \pm 3.18 \text{ Ra } (n = 269) \text{ depending on choice of data.}$$

If backarc basins are removed, then

$$R = 9.00 \pm 3.17 \text{ Ra } (n = 147), \text{ or}$$

$$R = 8.46 \pm 2.75 \text{ Ra } (n = 146).$$

The standard deviations (~ ± 3 Ra) are as significant as the means (which are 1 Ra unit higher than the conventional ‘biased’ value). The values imply that many so-called ‘plume-influenced’ or ‘lower mantle’ samples, are unexceptional and can be drawn from the same population as MORB.

New ridges (north Atlantic, Red Sea, backarc basins) tend to have higher values than mature ridges and abandoned ridges tend to have lower values. The statistics of R may therefore have more tectonic, local or temporal significance than global significance. These results are tabulated in Tables 1 to 3.

The most important result is simply the statistic for the mean and standard deviation of the entire dataset, the Grand Average. The mean is significantly higher than the usually quoted 8 ± 1 Ra. The data are more normally distributed, and σ is more than three times higher than the usually quoted estimate (based on filtered and truncated data). To check the robustness of this result, I eliminated data from Ethiopia (a new spreading center), obtaining 9.22 ± 3.32 ($n = 463$), and then eliminated the entire region of the North Atlantic supposedly affected by the Icelandic plume, obtaining 8.93 ± 2.85 Ra. The main result survives; the mean and standard deviation are much higher than estimates based on the hypothesis-dependent 'filtered', or biased, datasets. This has an immediate and dramatic implication. It means that values as high as 14 to 16 Ra are within 2σ of the "upper mantle mean." Many recent papers use R values as low as 11 Ra as "unambiguous evidence" for a lower mantle component. A large fraction of the so-called 'hotspot' volcanics fall within the spreading system range. The main exceptions are the more extreme values ($R > 20$ Ra) found in Iceland, Loihi and Samoa. These also do not demand a lower mantle component since the onset of rifting seems to be accompanied by high $^3He/^4He$ ratios (but extremely low [He] concentrations). A shallow U-poor region, sampled at the onset of cracking or tearing, cannot be ruled out (Anderson, 1998a, b). This high-R component appears to be missing at steady-state ridges and 'hotspots' that have been abandoned by ridges and HIMU islands, or the component is overwhelmed by the higher [He] later eruptives. Also given in Table 1 are results for all the Pacific spreading ridge data. This is similar to the global grand average and to subsets of the global data. There is no obvious spreading rate dependence. The age, or maturity, of the spreading feature seems to be more important. Note that the median is a more stable estimator of the $^3He/^4He$ ratio than the mean. So-called 'hotspot influenced' sections of the global ridge system are summarized in Table 2. These are regions affected by ridge reorganization, ridge propagation, and fracture zones. They seem to be drawn from the same population.

Subsets of Data

Systematic sampling has revealed that the $^3He/^4He$ ratio can be remarkably variable over short distances (e.g., Graham et al., 1993; Farley et al., 1993; Schilling, 1986; Kurz et al., 1998).

Changes apparently occur at fracture zones, in different flows in volcanoes of different ages, or near propagating rifts (Poreda et al., 1993). There are also rapid changes in R with time (Kurz et al., 1987; Farley et al., 1993).

Seawater (R = 1 Ra) and seawater affected sediments and crust are at the top of the oceanic column. Terriginous sediments and crust are expected to have low R (high U, Th-contents). Pelagic sediments, in regions of slow sedimentation, can have high R because of the influx of He-rich IDP (Anderson, 1993). The lithosphere may have low-R (if metasomatized) or high-R (for U, Th-poor restite). A metasomatized region, or a region which collects recycled material and residual melts (perisphere), may underlie the plate. This is expected to have low-R. Some parts of the shallow mantle, above about 60 km, may collect CO_2-rich gases expelled from rising magmas, or degassing dikes. Below these residual, refractory or enriched regions is the MORB reservoir which itself may contain inhomogeneities of various scales and may be radially zoned in composition. One therefore expects R to evolve with time and one expects samples collected at the onset of rifting or at fracture zones, seamounts, microplates or backarc basins, to differ from samples at mature steady-state ridges, or abandoned ridges.

Once an unbiased data set for the world ridge system has been compiled, various subsets of the data (new ridges, fast spreading ridges, backarc basins, etc.) or other datasets (ocean island basalts, continental flood basalts, etc.) can be tested against the Grand Average to see if they are significantly different. Tables 1 and 2 summarize various subsets of the spreading ridge data plus oceanic island data (data from Farley and Neroda, 1998, and references therein).

Conclusions Based on Filtered Data

Once the ^{3}He/^{4}He dataset is ‘filtered’ to remove samples perceived to be contaminated by plumes, one can no longer view certain values as ‘significantly’ higher or lower than MORB. "Significantly" is a statistical term and implies an unbiased sample. It is also common, but erroneous, to compare maximum values from some regions, with the MORB average and to declare that an anomaly has been found (even if samples of similar R are found along the ridge).

For example, the average ratio for a suite of EPR glasses was determined by excluding values greater than 9 Ra, yielding

$$8.26 \pm 0.19 \text{ Ra.}$$

Samples north of 16°S on the East Pacific Rise (EPR) having values of 8.6 to 10 Ra were then viewed as “significantly higher than this ‘normal’ value” (Kurz et al., 1996).

In the south Atlantic near-ridge seamounts have ^{3}He/^{4}He up to 11 Ra “significantly higher than adjacent ridges”, according to some authors.

Glasses from the Central Manus Basin have ‘typical plume ^{3}He/^{4}He ratios’ that cluster around 12.2 Ra, “a value significantly higher than the range found in most MORB, 8 ± 1 Ra” (MacPherson et al., 1998). The Manus backarc basin spreading center yields

$$R = 10.7 \pm 3.4 \text{ Ra } (n = 29)$$

for the mean and standard deviation. This differs from the value given in the original paper because the authors eliminated MORB-like helium ratios before calculating the mean and standard deviation of the remaining data. These results are similar to new ridges elsewhere.

Continental flood basalts have very low ^{3}He but some, having “^{3}He/^{4}He ratios higher than MORB”, confirm “the presence of plumes” in the Siberian, Deccan and Ethiopian flood basalts (Marty et al., 1996, 1998; Basu et al., 1993, 1995).

Discussion

Previous summaries of helium data for MORB include 85 samples (Zindler and Hart, 1986) to 158 samples (Hilton et al., 1993). My result, 9.06 ± 3.26 Ra, involves 456 samples, with similar results for the alternate smaller datasets.

My results for Pacific MORB (Table 1) bracket the Pacific estimate of Hilton et al. (1993) who obtain 8.68 ± 0.63 Ra (n = 30).

The mean has stayed about the same while the σ has increased because recently-obtained data along the EPR are higher than previous measurements, and backarc basin ridges and near-ridge seamounts have been included. Low values are found along the Chile Rise. The Galápagos and Easter microplate regions can be considered anomalous because of high R values, or as normal values of the shallow mantle when sampled at propagating rifts and unstable spreading boundaries rather than steady-state ridges.

A student t-test shows that the Hilton et al. (1993) estimate can be considered to be drawn from the same large population having the mean that we estimate. Interestingly, if we exclude the backarc basin data, the Hilton mean appears, statistically, to be drawn from a different population. It errs on the high side, meaning that the inclusion of the Chile Rise and near-ridge seamount data have an important influence on estimates of shallow mantle chemistry.

The large standard deviation associated with the present estimate merits comment since it is so much larger than the widely quoted value of ± 1 Ra based on the filtered, or 'hypothesis dependent', datasets. Even when all the shallow and high-R samples are removed from the database, I obtain ~8 ± 1.4 Ra for ‘filtered’ MORB (Table 1). The mean is the same as the usually quoted value, but the S.D. is much larger. It turns out that the usually quoted value (± 1 Ra) is based on individual ridge segments, which often tend to be uniform and have small S.D.

However, the means from segment-to-segment or from ocean-to-ocean vary from about 7.8 ± 0.5 Ra to 8.7 ± 0.6 Ra for south Atlantic and Pacific Ocean MORB, respectively (Hilton et al., 1993), and some smaller subsets of ridge data vary even more. The intra-ocean variation adds considerably to the standard deviation of the MORB estimate. Even if 8 Ra is accepted as the 'global mean' of MORB (based on the 'filtered' dataset) a change of the σ from ± 1 to ± 1.5 Ra means that a value of 11 Ra is within 2σ of the mean, rather than "being significantly higher than the MORB average" and 'therefore' indicative of lower mantle involvement.

The following are the [He] weighted means = {He} of some of the 'anomalous' ridge systems:

Azores	8.72 Ra
South Atlantic seamounts	8.68 Ra
Shona	8.67 Ra
Bouvet	8.41 Ra
Galápagos	8.79 Ra
Easter	8.80 Ra.

The corresponding medians are 8.70, 10.53, 8.39, 7.88, 8.47 and 8.38 Ra. Except for the median of the south Atlantic seamounts, all of these so-called 'plume influenced' regions are very close to 'normal' MORB by these measures. The mean of the seamount data is 9.77 ± 1.40 Ra, and the t-test shows that it can be of the same population as MORB.

The statistics of the so-called plume influenced regions of the global spreading ridge system argues against the plume hypotheses. The $^3He/^4He$ ratios of many oceanic islands are also well within the MORB range.

Low $^3He/^4He$ regions include; Shimada Seamount (abandoned ridge), São Miguel -

St. Helena - Tristan da Cunha (previously ridge-centered), Circe, Cook-Australs, Mangaia, Tubuai, Rarotonga, Heard, Jan Mayen, Canaries, Fernando, Cameroons, Guadalupe (abandoned ridge) and Kerguelen (formerly ridge-centered). These regions are all inactive or low activity and may reflect the waning of crack or stress controlled volcanism. Many of these regions are along fracture zones. Jan Mayen and Kerguelen may be continental fragments. There is little geophysical evidence that these are hot areas or are held up by plumes. The assignment of these volcanoes to "low-^{3}He" plumes is strictly *ad hoc*. Statistics of small samples and prior history of sampling appears to explain the variations along the global spreading ridge system.

Plum Pudding or Perisphere

Several models have been discussed for the geometry of heterogeneity in the 'upper' mantle. The plum pudding model proposes that enriched plums are embedded in a depleted matrix, and these are preferentially removed at 'hotspots' prior to sampling by the ridge system (Morgan and Morgan, 1999).

In the perisphere model parts of the mantle are preferentially enriched in incompatible and recycled material, and trapped melts, and this part of the mantle is the main contributor of geochemical 'anomalies' to new rifts and at the onset of seafloor spreading and at midplate volcanoes (Anderson, 1998c).

In both cases there is an enriched component that is preferentially removed at the early stages of magmatism. In the statistical treatment it does not matter whether the mantle is laminated, or stirred or permeated with plums. It is an urn, with various balls of various properties, which is sampled by various processes (grab samples, steam shovels, tweezers -- i.e.

seamounts, ridges, xenoliths). The statistical question is; Are the various subsets of samples drawn from the same population?

Two of the standard tests are:

1. Is this sample more than 2 (or 3) standard deviations from the mean? What are the odds of this?
2. Do the mean and standard deviation of a population (e.g., basalts around the Easter microplate, or the Azores, or the Galápagos) imply that it cannot be from the MORB-, or spreading ridge, population? I use the t-test in this regard.

“Hotspots”

This discussion uses data compiled by Farley and Neroda (1998) and references therein. See also references in the tables. The so-called “high-^{3}He” hotspots (they are actually low-^{3}He) are defined on the basis of some (usually, very few) of the samples (glasses, xenoliths) falling outside the perceived ‘normal’ MORB range. Some samples (or islands) in the following regions are designated as high ^{3}He/^{4}He (>11 Ra) hotspots; Hawaii, Galápagos, Iceland, Easter, Societies, Samoa, Azores, Juan Fernandez, Réunion and Pitcairn. MORB-like He ratios also occur in most of these regions, and the ratios often exhibit dramatic temporal and spatial variations. Most of these regions are more active, and have younger volcanoes, than the low R regions. Many oceanic islands either have higher than MORB or lower than MORB ratios (Farley and Neroda, 1998); only a few straddle the ‘MORB range’ (as previously defined). This may represent a temporal situation, with the high R islands tapping a shallower, or expendable, source. The temporal evolution in both the ridge environment and the midplate environment is from high to low R, suggesting a shallow LONU source that is expended early or is easily overwhelmed by deeper high-[He] basalts, such as ‘normal’ MORB.

The following islands and regions have median values of R that fall well within the MORB range; Kerguelen, Heard, Prince Edward, Jan Mayen, Canaries, Madeira, São Miguel, Gough, Haleakala, Hualalai, Galápagos, Rocard, Gambiers, Tubuai, Rurutu, Pitcairn, Mas Afuera, Ethiopia and Yellowstone (Farley and Neroda, 1998). Thus, by this measure, many of the so-called ‘high-^{3}He’ hotspots are not distinct from MORB. Even Hawaii, the classic 'high-^{3}He' hotspot, has individual volcanoes, and flows, that are indistinguishable from MORB. It is unlikely that the Hawaiian chain, or even the island of Hawaii, is underlain by a 'high-^{3}He' source but quite plausible that there are LONU domains in the lithosphere or shallow mantle (LONU, low [He]). Xenoliths claimed to be Archean in age have recently been found in Hawaiian basalts (Ducea and Sen, 1999). If this is true, an obvious source for LONU, high-R material has been found. Many oceanic plateaus appear to be underlain by ancient continental lithosphere.

Mauna Kea, Kohala, and the past 10,000 years of Mauna Loa lavas, are in the MORB range. Hualalai has higher R than these, although it is further from ‘the plume’. This suggests that it is not motion of the plate away from ‘the plume’ but activation of new faults and tapping of new shallow mantle that is responsible for the temporal change.

Although some basalts in the Galápagos area have ^{3}He/^{4}He ratios as high as 22.87 Ra, there are very low values nearby. The median value is 8.51 Ra. The samples having values near 8.5 Ra have one or two orders of magnitude more helium than the high R samples so any blending, as in a magma chamber, would return values near 8.5 Ra. The [He] weighted mean is {8.79} Ra. Similarly basalts in the Easter microplate area range from 7.7 to 11.67 Ra with a median value of 8.84 Ra. The weighted mean, taking into account [He], gives {8.8} Ra. Azores samples, although having values as high as 11.3 Ra, have a median of 8 Ra and a {He} average of {8.72} Ra, the high R basalts having an order of magnitude lower [He].

Continental Rocks; Ancient Rocks

Values of R well within the MORB range have been found in the Deccan Traps, east Greenland basalts and Archean komatiites. The highest values have been attributed to plumes because of the perception that "they are significantly higher than the MORB average," (Basu et al., 1995; Marty et al., 1998). It is not statistically valid to compare maximum values in one population with mean values in another. There are statistical methods for determining, from the means and standard deviations, if two populations differ.

A series of recent studies on continental rocks such as flood basalts, carbonatites and komatiites indicate extreme diversity, extraordinarily low ^{3}He contents and very low values of R (Table 3). Attention has focused on the one, or few, grams that yield high ^{3}He/^{4}He ratios. These high values are taken as evidence of a plume component and are used to characterize 'the lower mantle'. The helium concentrations in these samples are measured in fractions of a picomole per gram. The standard deviations of R in these old samples are typically 50%, or more, of the mean, not much different than modern samples. Surprisingly, the maximum values are typically 20 to 30 Ra, much the same as modern values in Hawaii, Iceland and Samoa. The standard deviation is not much greater than exhibited by fine scale sampling of seamounts, xenoliths or inclusions. I take the statistics to reflect the vagaries of small scale sampling and small sample statistics, and to reflect the variations intrinsic to the crust, lithosphere and shallow mantle.

Ancient mantle reservoirs will have had higher ^{3}He/^{4}He ratios than the same reservoirs today, and if gases from these reservoirs, or their magmas, were trapped in low-U, Th lithosphere, the R will be higher than contemporary magmas. The MORB source, for example, would have had a mean R much greater than 8 to 10 Ra when the carbonatites and komatiites were emplaced. The range of values will also be different. I have shown that values of 16 Ra are not exceptional when found along the current spreading ridge system. Much higher values would have occurred along the ancient ridge systems. One cannot compare values in ancient rocks directly with values in modern rocks, or modern reservoirs. Estimates of the rate at which R in the MORB reservoir declines with time vary widely (Anderson, 1998b) but, roughly, 'hotspot' type high-R can decline to 'typical' MORB-like values in 10^8 to 10^9 years. This depends, of course, on the $^{238}U/^3He$ and U/Th ratios.

After emplacement, the R of a rock will also evolve with time, if there is local U and Th, or atmospheric or seawater contamination. However, this is also the case for recycled material that enters the shallow mantle, and for magmas that ascend through the shallow mantle and crust. Surface processes apparently contribute to the diversity of components found, or inferred, in both MORB and OIB.

For comparison, in Table 3, I show results for two contemporary islands, Heard (Hilton et al., 1995) and Galápagos (Graham et al., 1993; Kurz and Geist, 1999). This shows that the statistics of ancient rocks are not much different than well sampled modern volcanic regions. It should be pointed out that the midocean ridge system is not sampled at this detail.

Some of the ancient rocks analyzed for helium are picrites and komatiites. Other isotopic systems place these squarely in the MORB camp (Anderson, 1994), and there is now doubt even if very high temperatures (outside the ridge range) are required to generate komatiites. There is also doubt that carbonatites are evidence for deep high-temperature mantle. Carbonatites have also been attributed to lithosphere or asthenosphere sources. In summary, the continental rocks discussed could also be termed ‘very low-^{3}He’, or ‘low- ^{3}He/^{4}He’ rocks. In diversity they are similar to some well sampled modern igneous formations.

Some ancient basalts have been attributed to plumes because some specimens have high R components. For example, the 55 Ma, post-breakup basalts in Greenland have R ranging from 6.8 to 10.7 Ra, but the median is 8.3 Ra (Bernstein et al., 1998). The plume explanation is put forward since the high values are “significantly higher than present day MORB”, indicating derivation from the undegassed lower mantle. This ignores the fact that values of 11 Ra are found along ridges. The Greenland values are not significantly different from the MORB mean established in this paper (8.7 $\pm$ 2 Ra, or 9.1 $\pm$ 3.3 Ra depending on whether basalts from the Easter, Galápagos and Bouvet regions are included). The value of 11 Ra is just about at the 2σ level, for the filtered dataset, implying that values higher than this can be expected about 16% of the time. Even with the older hypothesis- dependent value of 8 $\pm$ 1 Ra for MORB, a value of 11 Ra is at the 3σ level and is not, as implied in many papers, an impossible value for MORB. It is, in fact, a typical value in the unbiased (unfiltered) spreading ridge dataset.

Possible Time (depth) Sequence

If it can be shown, statistically, that some new ridge segment (say the Red Sea, or East African Rift, or Gulf of Aden, or Iceland) differs significantly from the global ridge average, then the question arises; Is this a ‘spatial thing’ (plume), or a ‘temporal thing’ (onset of rifting) or a ‘depth thing’ (LONU shallow mantle; recycled lithosphere)?

The life history of a midocean ridge involves birth (usually by ridge propagation), mature or steady-state, and abandonment. Mature ridges, characterized by steady-state magma chambers and prior loss of easily removed or shallow components, can be expected to differ from the initial and terminal stages of spreading. The initial stage is well studied but differences from “normal MORB” are almost invariably attributed to ‘plumes’ and ‘lower mantle involvement’ rather than to the normal stages of ridge development and initial or shallow mantle sampling. The absence of precursory uplift at the site of initial rifting, or rift extension, would argue against the plume hypothesis, or any thermal explanation.

Table 2 summarizes several compilations of data that may have bearing on this. “New” ridges seem to be characterized by high R (~10 Ra) whether they grow by end-on propagation of pre-existing ridges, or in backarc basins. They are similar, in R, to the south Atlantic seamounts, which may also tap shallow mantle, undiluted by massive axial magmas.

Abandoned ridges, and islands abandoned by ridges, have low R (6-7 Ra) and may reflect melt depleted, or residual, shallow mantle, or ‘contaminated’ mantle. These values are similar to the South Chile Rise and Pacific seamounts, nominally different environments.

HIMU islands are supposedly affected by altered oceanic crust and sediments, or fluids therefrom. They have low ^{3}He/^{4}He ratios in accord with the inferred high ^{238}U/^{204}Pb ratios (high μ) and presumed high ^{238}U/^{3}He (high ν). They may tap a source similar to that tapped by abandoned ridges and ridge abandoned islands, or the South Chile Rise (which is near the South Chile subduction zone). The so-called EM islands have R = 7.89 $\pm$ 3.63 Ra, similar to the North Chile Rise, a ridge-fracture zone system.

It appears that, initially, ridges tend toward high R while abandoned ridges, and islands, tend toward low values. This suggests that the shallower, or easier to remove, or initial, heterogeneities have high ^{3}He/^{4}He ratios. Whether these high R regions are shallow “lithosphere” or embedded “plums” is open for discussion. Their generally low [He] suggests that they must be shallow since they would be overwhelmed by a N-MORB component, which is probably sequestered at greater depth and certainly involves larger volumes of mantle, and more extreme melting. A shallow, high R, low [He] and refractory source seems to be indicated, perhaps lithosphere, or recycled lithosphere (the complement to recycled HIMU crust).

The association of high $^3He/^4He$ ratios with early stages of magmatism (Hawaii, Juan Fernandez, Greenland, Deccan,…), fracture zones, young oceans (Red Sea, Gulf of Aden), rifts (Ethiopia), caldera collapse and tectonic uplift (Yellowstone), reorganizing plate boundaries (Bouvet, Shona), new and unstable backarc basins (Lau, Manus), and low ratios with abandoned ridges (Socorro, Gough, Tristan da Cunha) suggest that high $^3He/^4He$ ratios (but low ^3He absolute abundances) may be a feature of the shallow mantle, perhaps U, Th-poor lithosphere, or restite layer. The liberation, or incorporation, of these shallow gases by initial fracturing and magmatism seems to be indicated by the tectonic context of high $^3He/^4He$ localities. Once the deeper gas-rich MORB magma becomes involved, then lower ratios, $^3He/^4He$ of 6 to 9 Ra, will dominate over the gas-poor high $^3He/^4He$ ratio sources.

'High' $^3He/^4He$ ratios (> 9, 9.5 or 11 Ra, depending on the author) are commonly called 'plume' or 'lower mantle' or 'primitive' helium. Because of the low [He] and low He/Ne and He/Ar ratios of these samples (Figure 2) and because of their temporal and tectonic context, they could, with more justification, be called 'lithospheric helium' (Anderson, 1998a, b). There is no evidence that they are derived from a deep, or an undegassed, reservoir. Buoyant lithosphere, or restite, is more likely to be able to retain ancient isotopic signatures than the 'convecting mantle'.

Onset of Rifting

Most midocean ridges are mature and steady-state. One can ask, What is the R at the onset of rifting, and does this differ from mature ridges? Ethiopia is probably the newest sampled ridge and yields 8.24 ± 5.41 Ra (n = 46). This cannot be discarded as a separate population based on the t-test, so in some of our runs, we incorporate it into the ridge dataset.

However, we can also combine it with the Red Sea, Kolbeinsey-Mohn ridges, Easter, Galápagos, Manus and Lau, as regions having new or propagating ridges, to obtain a ‘new ridge’ datum. The result is 9.93 ± 4.3 Ra (n = 207). If we add Iceland, because of the constant and recent ridge jumps in this area, the value only changes slightly; 10.01 ± 4.66 Ra (n = 239). These estimates are statistically different from the global average. Note that "new ridges" (Table 2) have a much higher variability than established ridges. This is expected since they are, in a way, 'midplate' and involve pre-existing crust and lithosphere, and previously undrained mantle.

There is only a small amount of data on abandoned ridges, but we obtain

6.09 ± 1.80 Ra (n = 9) from the compilation of Graham et al. (1992).

These results are consistent with a shallow LONU region and a low R residual mantle. The LONU source seems to be exhaustible and transient.

The north Atlantic, Red Sea, Gulf of Aden and the south Pacific microplates formed by end-on ridge propagation rather than pull-apart. The early magmas in these regions may tap shallow mantle preferentially, and yield more diversity than is possible at a steady-state ridge. The fact that the high ^{3}He/^{4}He basalts found in these new ridge areas have low [^{3}He] is consistent with a shallow low U, Th-source, rather than a high [^{3}He], undegassed source.

Continental breakup (push-apart) is often attributed to deep mantle plumes, but in the above cases the processes of plate divergence involve rotation and end-on propagation and represent the present location of a propagating crack, rather than an initial break. Older ridges may well be different geochemically than early ridges, or narrow oceans. Initial magmas may be contaminated by shallow sources (air, seawater, crust, lithosphere, perisphere) or by 'plums' (the plum pudding or marble cake models). The perception that the "MORB-mantle", or "Depleted Upper Mantle" or the "convecting mantle" is homogeneous is based on biased statistics.

Iceland

Iceland is generally regarded as the top of a deep mantle plume, but it may also be a transient edge effect associated with the extension of the central Atlantic ridge along an intracratonic suture. This is a region of relatively new seafloor spreading, a narrow ocean and constantly shifting plate boundaries. The magma geochemistry reflects reworking of thick crust and possibly shallow mantle. Iceland is close to the pole of rotation of the American and European plate and hence is slow spreading. It is bordered to the north by fracture zones and islands of continental affinity. One might expect under these circumstances to be able to sample the shallow mantle in a way not available to mature rapidly spreading ridges in the middle of wide oceans. Additionally, the highest temperature magmas in Iceland are isotopically indistinguishable from normal MORB (Anderson, 1994). Mantle temperatures in the North Atlantic, and during eruption of the Greenland basalts are not particularly high (Favela and Anderson, 1999; Korenaga, 2000). The volume of the eruptives appears to be caused by focusing, not high temperature. This is called the EDGE effect (Edge Driven Gyres and Eddies) (Anderson, 1998c).

Our view is that it is better to treat Iceland as a possible end-member of a ridge, because of its location and history, rather than eliminate its materials from the spreading ridge database because of its diversity and preconceived notions about the allowable range of shallow mantle geochemistry. Some low values of R are found in Iceland and along the fracture zone to the north (Condomines et al., 1983; Schilling et al., 1999). This rules out the pervasive, and long-distance, transport of Iceland high-R plume material, as has been invoked for the Reykjanes Ridge (Condomines et al., 1983; Schilling, 1986). An unstable system of ridges and triple junctions, and transient, and local, tapping of a shallow LONU source seems to be indicated. The association of geochemical anomalies with fracture zones is as defensible as their association with 'hotspots', many of which are merely elevated portions of fracture zones or ridge-transform intersections. A tectonic and shallow explanation for features associated with Iceland is given in Favela and Anderson (1999) and Keller et al. (1999).

Mixing

The high R samples are generally low [He] and would therefore be swamped if they were put into a midocean ridge magma chamber or intruded by normal MORB. For example, I took a subset of the ridge data composed of 165 samples having a mean R of 8.72 Ra. To this, I added the samples from the Kolbeinsey Ridge (n = 30), Iceland (n = 32) and 16 of the highest R basalts from Loihi and Hawaii. The composite was mixed and weighted by the [He] concentration of each sample to obtain {R}. The average changed from 8.72 Ra to {8.80} Ra for this mix, which was about two-thirds MORB and one-third “high-^{3}He hotspot” material. Except for the [He] content, all samples were assumed to be the same size. Thus it is clear that in finding the full range of R that may occur in the upper mantle, one must go to ‘anomalous’ places, such as slowly spreading ridges, fracture zones, unstable triple junctions, seamounts and reorganizing plate boundaries such as jumping or propagating ridge segments. Finding 'anomalous' values at these locations is not evidence for a deep mantle plume. The apparent homogeneity of MORB at ridge axes may be a result of magma chamber processing rather than an intrinsic characteristic of the upper mantle.

It is commonly assumed in geochemical box models that a homogeneous well-stirred depleted ‘reservoir’ occupies the entire upper mantle, extending right up to the base of the plate. It is well known, however, that metasomatic fluids, residual melts, the mantle wedge and recycling also affect the shallow mantle, and that N-MORB does not appear at the onset of rifting but only after a period of spreading. It is OIB-like magmas that occur in all tectonic environments, even convergence zones, and regions of localized extension. When the overlying crust and lithosphere and enriched shallow mantle is cleared away, then ‘normal’ uncontaminated MORB makes an appearance. Because of the multiple and contradictory usages of ‘lithosphere’ and ‘asthenosphere’ (Anderson, 1995), I refer to the outer shell overlying the MORB reservoir as the ‘carapace’.

Ironically, the reference state for both plume modeling and passive spreading is a static isothermal mantle. Plumes are invoked in geodynamic models to introduce a thermal anomaly while they are invoked into the geochemical models to introduce chemical anomalies into 'the convecting mantle'. These are contradictory views. A non-static, non-isothermal, non-homogeneous evolving upper mantle should be the reference state in both dynamic and geochemical modeling. The upper mantle cannot simultaneously be static and isothermal, and well-mixed and convecting.

If the carapace is under horizontal compression, it is unlikely that melts from the underlying magmasphere can escape via dikes and volcanoes. Fluids in and below the carapace can escape in regions of horizontal extension, such as near ridges, in young lithosphere, at forearcs and backarcs and in extensional outer rises around volcanic loads. Transiting fluids can pick up gases and impurities from the various regions of the carapace. A depleted garnet-poor carapace can be considered a candidate for a long-term isolated reservoir, or source of LIL (crustal and melt metasomatized parts) and gas (from trapped fluid-filled inclusions). Initial magmas penetrating such a carapace will differ from later magmas. Temporal and spatial variations can be expected in such an environment.

Provenance

Ocean island and continental flood basalts are characterized by enriched or radiogenic isotopic chemistry for the heavy LIL elements and, in many cases, for helium as well. In the view of rare-gas specialists, however, the most unambiguous indicator of ‘undegassed plume material’ is high ^{3}He/^{4}He ratios, inferred to require an excess of non-radiogenic helium. Since ^{206}Pb, ^{207}Pb, ^{208}Pb and ^{4}He (and heat) are all daughter products of U and Th, we have the paradoxical situation that a U-rich region is required for the heavy isotopes (and implied for 'hotspots'), and a U-poor region is required for helium (and neon). The ‘primordial undegassed lower mantle’ model addresses this paradox by neutralizing the large amounts of ^{4}He expected in an ancient primordial reservoir with very large amounts of the primordial isotope, ^{3}He. The amount of ^{3}He required is comparable to the amount in primitive carbonaceous chondrites. This brings up another paradox. The Earth is very depleted in volatiles compared to chondrites, but helium, the most volatile of all, must be an exception to this rule. This is the ‘undegassed lower mantle’ model. A problem is that all high ^{3}He/^{4}He materials have very low ^{3}He concentrations compared to midocean ridge basalts which, in this model, are from a ‘degassed’ reservoir. The Helium-Heat Flow Paradox is a related paradox.

One could recognize, alternatively, that although He, U, Th, Rb, Sr, Pb etc. are incompatible elements in that they enter magmas when the mantle melts, they differ in that gas exsolves from the magma at shallow depths, and He-CO_2 can separate from U-Th. Some fraction of the exsolved gas is stored in crystal cumulates and fluid-filled inclusions in refractory peridotite. Dike tips are low pressure environments and gas might exsolve from propagating dikes at greater depths than from magma chambers. In any case, magmas can retain their U and Th but can degas their complement of volatiles. Deeper exsolved gas can, in part, stay in U-Th poor surroundings. Both the gas and the magma initially have the same $^{3}He/^{4}He$ ratio, and the same as the magma source, but as time goes on, the helium stored in a low $^{238}U/^{3}He$ (LONU) environment, such as fluid filled inclusions, or in olivine grains, will retain high ratios, while the frozen magma (crust) and original reservoir (MORB-source?) will continue to generate ^{4}He and will evolve to low $^{3}He/^{4}He$ ratios. The fluid filled inclusions will have lower He/Ne (and He/Ar) ratios than the partially degassed magmas, or the source, because of the higher solubility of He in the melt. This is a property of high R basalts (Anderson, 1998a, b, c). Low [He], He/Ne, He/Ar and high but variable R can be considered as properties of lithospheric helium (Figure 2). "Plume helium" from a hypothetical primordial undegassed reservoir should have high [He] and high He/Ne and He/Ar (as well as high He/Sr, He/Pb, He/CO_2, etc.) ratios. Such a component is not evident in high R basalts.

Helium Incompatibility

Helium is not the same kind of incompatible element as U, Th, Pb, Sr, Nd, Rb, Sm and Hf, the other common elements and isotopes used in discussions of mantle geochemistry. Helium is incompatible in that it prefers to enter the melt when a rock is melted. However, as a magma rises, it degasses, and at this point He can decouple from the other LIL, in particular U and Th. Magmas wet grain boundaries and can escape to the surface. Some fraction of the helium (with its CO_2 carrier) escapes the magma and ends up in magma chamber cumulates and in the lithosphere. These are low U, Th environments compared to magma or basaltic crust, and gas trapped in fluid-filled inclusions will evolve isotopically less rapidly than the gas in the original MORB reservoir. In the plum-pudding model, some plums may be large refractory olivine-rich domains, and the He in these domains will also retain high $^3He/^4He$ ratios compared to ‘enriched’ (U-rich) domains. However, it is easier to envisage lithosphere, recycled lithosphere and melt depleted cumulates as long-term storage reservoirs for LONU material. Thus, helium is ‘melt-incompatible’ at shallow depth, and some fraction of exsolved He-CO_2 will enter the lithosphere, thereby acting as a ‘compatible element’, along with Os. It may be that the only geochemical tracers that involve 'clean' lithosphere are osmium and helium isotopes. Although there may be little helium stored in the lithosphere, very little is needed, compared to the ridge and arc flux, and a modest, exhaustible source is what is needed to explain the very low ^3He contents of midplate volcanoes and the temporal trends toward MORB-like $^3He/^4He$ ratios. When deeper (MORB) gas-rich magmas become involved, the lithospheric signature is quickly swamped (the same would hold true for many plume components). In order to ‘restart’ a high R event, a new crack (Iceland) or a new volcano (Loihi) must be initiated. A shallow high R, low [He] source explains the lateral and temporal variability of ‘hotspot’ helium, plus the eventual takeover, in many cases, of gas-rich MORB geochemistry. Helium may also be more compatible, in the traditional crystal-melt sense, than U and Th (Graham, 1988). If this is the case, then residual crystals would have higher He/U ratios than the source, and these would also evolve to high R reservoirs.

Note that the shallow LONU reservoir is not the same as the (possibly deeper) perisphere. The perisphere, like the mantle wedge, metasomatized lithosphere and oceanic crust, is LIL rich while the LONU source is LIL and volatile-poor, being characterized geochemically by small amounts of trapped (He, CO_2) gas and low $^{186}Os/^{187}Os$, and probably, unique $^{208}Pb/^{204}Pb$ ratios. The $^{238}U/^{3}He$ ratio may be influenced both by crystal-melt and melt-vapor partitioning.

LONU may also be thought of as complementary to HIMU (high $^{238}U/Pb$), which is widely believed to be recycled fragments of oceanic crust. LONU may be recycled fragments of oceanic (or continental) lithosphere. It is also possible that LONU may be ancient mantle trapped in the ocean basins as roots of plateaus and swells, such as has been proposed for Kerguelen, Seychelles, Lord Howe Rise and Ontong-Fiji (Nur and Ben-Avrahem, 1982).

Arguments for a Shallow Source for LONU

There are various lines of evidence suggesting that the low $^{238}U/^{3}He$ (LONU) source (usually called the 'high-^{3}He' or 'undegassed' or 'plume' source in the geochemical literature) is shallow:

1. the time sequence (Hawaii, Juan Fernandez, Galápagos) of high R basalts initially, followed by MORB-like R suggests that the high $^{3}He/^{4}He$ source is shallow.
2. the rapid lateral variations, which put so-called 'high-^{3}He' basalts (actually low ^{3}He, high $^{3}He/^{4}He$ ratios) within 10's of km of low $^{3}He/^{4}He$ basalts (or geothermal areas).
3. the existence of high [He] and high R lithospheric xenoliths (Farley and Neroda, 1998; Poreda and Farley, 1992) and inferred Loihi-like noble gases in continental lithosphere (Ballentine, 1997).

These observations are not predicted by the plume hypothesis. They have been 'explained' by invoking a radially zoned or toroidal plume, drifting of a volcano off of a high R plume, entrainment of 'normal' mantle and emplacement of plume material into the lithosphere. None of these *ad hoc* explanations account for the very low ^{3}He in high R basalts, the rapid variations in R, and the indifference of R to magma or xenolith chemistry or location relative to a 'plume axis'.

Backarc basins (Lau, Manus) and geothermal systems above deep crustal batholiths (Yellowstone) commonly have variable R, but a few of the samples are high R, indicating a shallow source. BAB are cut off from the deep mantle by slabs, and it is unlikely that low [He] material could pass through U and Th-rich batholiths.

The fact that ‘normal’ MORB values occur at spreading ridges and fracture zones adjacent to purported ‘plumes’ (Red Sea, Wolf Darwin Rise, Azores, Shona, Bouvet, Easter, St. Helena, Amsterdam, Iceland) indicates that high R island gas is from shallow depth and has low ^{3}He contents. Otherwise it should overwhelm the ridge signature. Proposed long-distance transport of high R material from Iceland down the Reykjanes Ridge is countered by the presence of MORB-like helium ratios in eastern Iceland and along the fracture zones to the north.

Samoa and Juan Fernandez are along major tears in the lithosphere having to do with dramatic changes in dip and/or strike of a nearby plate boundary (Favela and Anderson, 1999). These are high R islands, on fracture zones.

The mantle xenolith population may not be representative of unmetamorphosed and intact lithosphere. Although many mantle xenoliths have large He-contents (up to 10^{-6} cc/gm), most have R/Ra in the ‘MORB-range’ 7-9. High ^{3}He/^{4}He and high gas contents occur in xenoliths from Samoa, Hawaii, Kerguelen, and high ^{3}He/^{4}He is inferred for some continental lithosphere. Metasomatized mantle (high U, Th) and mantle in fracture zones and sutures may be most easily fragmented and brought to the surface.

The highest ^{3}He/^{4}He ratios (> 15 Ra) in Yellowstone are on the edges of a caldera overlying a silicic magma chamber, highly enriched in U and Th and which has erupted vast quantities of rhyolite. If the source of helium is deep, then the crust and magma chamber must be essentially transparent to deep helium (Craig et al., 1978). Alternatively, the rapid local uplift and the rapid lateral variations in R (Kennedy et al., 1985) suggest a fracture conduit to a shallow LONU source.

The idea that there cannot be ancient trapped gases in the oceanic “lithosphere” assumes that all material in the oceanic “crust and lithosphere” formed in the last 200 My. Some of the plateaus and swells in the oceans, however, may be ancient, or have continental roots (Nur and Ben-Avrahem, 1982). Evidence for isotopic isolation of order 1 Ga is not necessarily evidence for a deep source since buoyant refractory peridotite may form the base of the Iceland, Kerguelen and Hawaiian swells. Archean age xenoliths have recently been found in Hawaiian basalts (Ducea and Sen, 1999). It begs the question (and immunizes the hypothesis against falsification) to claim that all such occurrences were emplaced by deep mantle plumes.

The Common Component

The isotopic composition of most OIB can be explained in terms of mixing between extreme endmembers; EM1, EM2, HIMU and DM. The high R basalts are not associated with any of these components but plot between these endmembers, closer to the depleted component (DM). This indicates that high-R is not carried by pelagic sediments (EM1), continental sediments or lithosphere (EM1) or altered oceanic crust (HIMU). The refractory residual left after extraction of basalt (and Rb, Sr, U, Th, Sm, Nd) is depleted and is a potential reservoir that is essentially immaterial for most isotopes and LIL but may be important for osmium and helium. On multiple isotope plots midocean ridge and island data form trends that appear to focus on a common component, similar to the component that carries a high-R signature (Hanan and

Graham, 1996). This suggests that the source of this component is shallow so that it can interact with magmas ascending through it, or evolving in it. A buoyant restite region, such as lithosphere, seems to be implicated.

Propagating Cracks

The tectonic context of so-called hotspots and hotspot tracks is discussed by Favela and Anderson (1999). The fan-shaped rift pattern near the Galápagos is the result of continuing fragmentation of the Farallon plate caused by divergent pulls of the Central and South American subduction zones. The Cocos, Nazca and Juan de Fuca plates are the remnants of the fragmenting Farallon plate and the ridges separating some of them started out as incipient volcanic cracks or leaky transforms which may have resembled current island-seamount chains.

The Juan Fernandez chain marks the southern border of the flat portion of the subducting Nazca plate and the volcanic gap in Chile. The plate is being torn by this change in dip angle.

The Samoan chain is due to a tear in the Pacific plate where it subducts beneath the Tonga trench to the south but continues as a surface plate to the north.

All of these regions are characterized by some high-^{3}He/^{4}He samples interspersed with samples having much lower R. The average of basalts from these regions is 11.75 ± 5.13 Ra (n = 57). This is similar to the value for "new ridges". The Manus Basin could also be considered a new crack or reorganizing ridge system.

The Cook-Austral island-seamount chain satisfies few, if any, of the predictions of plume theory (Dickinson and Green, 1998) and is best thought of as stress or fracture controlled magmatism. McNutt et al. (1997) showed that several generations of volcanoes exist in this area, and volcanism started when this section of the plate was at a ridge. In contrast to Samoa and

Juan Fernandez, the Cook-Austral chain may represent a reactivated old fracture. The Cook-Austral chain is characterized by relatively low R (Table 2).

Is there any independent support for the idea that the high ^{3}He/^{4}He ratios found at the onset of rifting in a variety of tectonic environments, and at propagating tears, are derived from the shallow mantle? First of all, the samples in all these environments are extremely low in [^{3}He]; they are not, as commonly expressed, “high-^{3}He magmas.” Secondly, high-^{3}He/^{4}He xenoliths are found in the Pacific lithosphere under Samoa (Poreda and Farley, 1992). Some of these xenoliths have 1 or 2 orders of magnitude more ^{3}He than high-R basalts. Finally, Ballentine (1997) found indirect evidence for a Loihi-type noble gas component in continental lithosphere.

The evidence in this paper is consistent with the presence of a low [He], LONU, high R region in the shallow mantle which is preferentially sampled at new cracks and ridges and during times of plate boundary reorganization or activation of fracture zones.

Lassiter and Hauri (1998) argue that Kea-endmember in Hawaiian basalts represents an ultramafic source, possibly recycled lower crust or lithosphere. The key evidence was provided by Os and O isotopes. Lithospheric and ultramafic rocks are very poor in U, Th, Rb and Sr and their isotopic tracers. The other endmember, Koolau, appears to be recycled oceanic crust and is expected to be high ^{238}U/^{3}He. The volcanoes bearing these names have helium ratios of 6-16 Ra. The ‘high-R’ volcanoes are between these endmembers on heavy isotope diagrams, but they exhibit secular trends, starting high and evolving to MORB-like R with time.

In the shallow LONU-low [He] model (Anderson, 1998a, b) a new crack or a new volcano can temporarily be high-R but a single crack system, or conduit, can exhaust the helium supply or be overwhelmed by the deeper gas-rich MORB magmas which always seem to show up at some point. A new crack system, or conduit, is required to maintain high-R. Regions such as Iceland or Easter, where ridges are jumping or propagating, locally have high-R magmas and gases. The amounts of ^{3}He coming out of so-called ‘hotspot’ volcanoes or contained in ‘hotspot’ rocks are extraordinarily low compared to the global ridge system and midocean ridge basalts. Marty et al. (1998) assume that the upper mantle cannot support magmatism for as long as 30-60 My or provide high-R basalts, episodically, for this period of time. But the Greenland-Iceland basalts contain orders of magnitude less [^{3}He] than MORB and also orders of magnitude lower [He] than some lithospheric xenoliths (e.g., Poreda and Farley, 1992). If these xenolith [He] concentrations are typical of unaltered lithosphere, the total amount of helium represented in the Greenland and Iceland basalts can be provided from a mantle lithospheric layer less than the thickness of the basalts even if He retention in the basalts is inefficient.

Evidence That LONU Is Not a ‘Primordial Undegassed Reservoir’

The total ^{3}He flux out of ‘hotspot’ volcanoes is much less than at ridges or island arcs (Sano and Williams, 1996). The discrepancy is about 3 orders of magnitude from prediction (Porcelli and Wasserburg, 1995).

The ^{3}He-content of MORB is usually more than an order of magnitude higher than OIB basalts.

The He/Ne and He/Ar ratios of MORB are higher than OIB (Figure 2), indicating that OIB did not lose their ^{3}He, prior to sampling, by gas exsolving from a magma.

The ^{3}He/^{21}Ne and ^{4}He/^{22}Ne ratios of MORB and OIB are complementary in the sense that OIB gases are to MORB gases as vesicles are to degassed magma. This suggests that ancient degassing events may have provided the gas (trapped in LONU refractory restite) that later contributes to midplate volcanoes (Anderson, 1998a, b).

When there are correlated He-Sr and He-Pb trends in oceanic island basalts, indicating mixing, the He/Sr, He/Pb etc. ratios are generally greater for the MORB component, indicating the so-called ‘plume’ component is from a ^{3}He-poor source.

The assumption that ^{3}He/^{4}He ratios of about 8 Ra are from the Degassed Upper Mantle (DUM) while ratios of greater than 11 Ra or so are from Undegassed, or Primordial Mantle, is based on the assumption that high ratios imply excess ^{3}He, and that high R, low [He] basalts have lost substantial amounts of ^{3}He. The basic assumption and the auxiliary assumptions do not seem to be true.

Degassing

Basalts with high ^{3}He/^{4}He ratios invariably have very low absolute helium concentrations, [He], including low [^{3}He]. Although quenched glasses having R of 20% to 200% higher than the 'MORB mean' are attributed to an 'undegassed reservoir' the actual [^{3}He] of such glasses is typically one to three orders of magnitude lower than in the gas-rich 'popping-rock' MORB samples. Gas loss is the common explanation, although some of the highest R rocks are found on the flanks of Loihi at 5 km depth, and these also have low [^{3}He]. The solubility of the noble gases in magma decreases with atomic weight. A degassed magma will accordingly develop high He/Ne and He/Ar ratios, and the vesicles, and lost gas, will have low ratios.

Figure 2 shows that MORB glasses have high [He] and high He/Ar ratios. If 'popping-rock' represents average undegassed MORB, then the MORB field can be explained by about an order of magnitude range in [He] in the parent magmas and 1 to 4 cycles of degassing. As

MORB-like magmas ascend at midplate environments they interact with olivine or trapped vesicles from prior degassing events, and with air and seawater. Figure 2 is not consistent with OIB having degassed more than MORB. The OIB field is consistent with mixtures of atmospheric gas, lithospheric gas (xenoliths) and MORB. OIB may simply be degassed and contaminated MORB.

But We Know They Are Plumes!

Some might object to the consideration of alternate explanations for many of the regions being discussed since they are well known to be ‘hotspots’ and require, on other grounds, a lower mantle source. However, the correlation of so-called ‘hotspots’ with fracture zones, transform faults, suture zones, new ridges, abandoned ridges, ridges in general, and continental margins is so strong that alternative mechanisms of volcanism need to be considered (Anderson, 1998c, d; Favela and Anderson, 1999). Bathymetry, gravity and heat flow considerations only require a shallow cause and often dictate against a thermal anomaly (Anderson, 1998d). The ‘fixed hotspot’ and ‘parallel hotspot track’ predictions have not held up (Favela and Anderson, 1999) and, in fact, at best, only applied to a small fraction of the extant ‘hotspots’. In many cases a noble gas ‘anomaly’ has been the only evidence for a plume and, as I have shown, there is circular reasoning in this identification. The only geochemical argument for “primitive” or “undegassed” or “lower mantle” status for some basalts is the assumption that high-^{3}He/^{4}He implies high-^{3}He, and that many basalts have R values “significantly higher than the MORB mean.” If 'significantly' means two standard deviations, then the present study requires that R exceed about 16.3 Ra, and most of the so-called 'plume' or 'lower mantle' samples can be considered to be drawn from the upper mantle, if midocean ridges tap the upper mantle.

Summary

The global spreading ridge system yields R = 9.06 ± 3.26 Ra for the mean and standard deviation. Since midocean ridges blend magmas from large volumes the upper mantle range for $^{3}He/^{4}He$ may be even larger. Most so-called high-^{3}He hotspots fall within the above range. 'High R' material is probably from the shallow mantle since it is most evident at the onset of rifting. There is no evidence that high $^{3}He/^{4}He$ ratios imply excess ^{3}He.

TABLE 1. Summary

$^3He/^4He$ Ratios = R / Ra

		n
ALL RIDGES	9.06 ± 3.26*****	456
exclude shallow depths (< 2.5 km)	8.50 ± 2.33	254
exclude R > 9.5 Ra	7.47 ± 1.95	303
exclude both	7.67 ± 1.35	193
exclude d < 2.5 km, R > 11 Ra	7.91 ± 1.50	212
exclude Easter, Galápagos, Bouvet	8.67 ± 1.88	219
NORTH ATLANTIC		
ALL	9.37 ± 2.45	36
exclude > 9.5 Ra	7.87 ± 0.69	24
PACIFIC		
ALL	8.84 ± 3.18******	269
exclude Backarc basins	8.46 ± 2.75*******	146

***** With slightly different datasets, I obtain

R = 9.14 ± 3.59 Ra (n = 503)

and

R = 9.23 ± 3.35 Ra (n = 457)

****** The alternate dataset yields 9.21 ± 3.40 (n = 210).

******* The alternate dataset yields 9.00 ± 3.17 (n = 147).

Data sources: Farley and Neroda (1998) and Graham et al. (1992, 1993, 1999) and references therein; also Poreda et al. (1986, 1993); Kurz et al. (1998); Moreira et al. (1995, 1996, 1999); Marty et al. (1996); Nishio et al. (1999)

TABLE 2. Statistics (mean ± s.d.) of subsets of the data and EM, HIMU and Low R islands.

Ridge abandoned islands (1)	7.10 ± 2.44
Abandoned ridges (2)	6.08 ± 1.80
"New" ridges (3)	9.93 ± 4.30
"New" ridges (4)	10.01 ± 4.67
EM islands (5)	7.89 ± 3.63
HIMU islands (6)	6.38 ± 0.94
HIMU, EM, Low R islands (7)	7.63 ± 3.33
North Chile Rise	7.78 ± 0.24
South Chile Rise	6.88 ± 1.72
Pacific Seamounts	6.58 ± 1.70
South Atlantic Seamounts	9.77 ± 1.40

Data from Farley and Neroda (1998) and references therein.

(1) Gough, Azores, Tristan, Heard, Kerguelen, Réunion

(2) Shimada, Socorro, Guadalupe

(3) Kolbeinsey, Mohn, Easter, Galápagos, Manus, Lau, Ethiopia, Red Sea

(4) Add Iceland

(5) Pitcairn, Cook-Austral, Societies

(6) St. Helena, Polynesia

(7) Above plus Hilton et al. (1995)

TABLE 3. $^{3}He/^{4}He$ ratios, normalized to air (1.38×10^{-6}) in older continental rocks.

	Average ± S.D.	Median	Range	n
Komatiites 2700 Ma	9.14 ± 13.6	0.4	.04 - 39	17
Carbonatites 380 Ma	11.77 ± 4.48	10.4	4.9 - 18.7	7
Siberia 253 Ma	6.53 ± 3.38	5.4	1.4 -12.7	19
N.E. Greenland 58 Ma	6.62 ± 6.66	3.46	1.1 - 22	11
W. Greenland 60 Ma	22.21 ± 11.46	28.05	4 - 31	5
Deccan 69 Ma	10.05 ± 4.65	11.45	3 - 14	4
Ethiopia 20 Ma	8.24 ± 5.41	8.65	.03 - 20	46
Heard Island	6.83 ± 5.20	7.15	3.9 - 18.1	16
Galápagos	12.39 ± 5.80	9.87	4.7 - 27	53

Data from: Basu et al. (1993, 1995); Botz et al. (1999); Graham et al. (1993, 1998); Marty et al. (1996, 1998); Richard et al. (1996); Kurz et al. (1998); Hilton et al. (1995).

Figure Captions

Figure 1: Histogram showing the global spreading ridge data and the data 'filtered' by eliminating shallow data. The traditional MORB value is 8 ± 1 Ra while the present results give a higher mean and a much larger standard deviation.

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

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