# Is "Primordial" Helium Really Extraterrestrial?

## K. A. Farley

$A$mong the isotope systems exploited by mantle geochemists to deduce the chemical evolution of the Earth, those of the rare gases are unique because they record the migration of volatile species from the mantle to the atmosphere. The isotopic composition of helium in mantle-derived rocks is now reasonably well known, and it suggests that this migration has been both more heterogeneous and less extensive than commonly expected. The implications of the helium data are profound, but they seem to conflict with widely held beliefs derived from other geochemical tracers, including the isotopic characteristics of lithophile elements (that is, elements such as Sr, Nd, and Pb found predominantly in Earth's silicate crust). Although the geochemical processes affecting the rare gases and lithophile species must be intimately related, it has proven difficult to reconcile them in any obvious way. On page 170 of this issue, Anderson offers a controversial hypothesis that can simultaneously explain all of these disparate tracers (1). If he is correct, a dramatic reinterpretation of the terrestrial rare gas data and their significance to planetary evolution is required.

The two isotopes of helium have very different sources within the Earth. Helium-3 is commonly thought to be "primordial," a vestige of the planet's original volatile inventory, whereas $^4$He is continuously produced by the radioactive decay of U and Th. As a result, the isotopic composition of mantle helium reflects the time-integrated ratio of a volatile species (He) to nonvolatile parent nuclides (U and Th). During mantle melting, helium is strongly partitioned from the solid phase into the melt and from the melt into a coexisting vapor; this processing can produce large variations in the He/(U + Th) ratio and hence the $^3$He/$^4$He ratio of the mantle. Just as lithophile tracers such as $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd record the timing and extent of partial melt extraction from the mantle to the crust, the $^3$He/$^4$He ratio records the migration of volatiles to the atmosphere. Importantly, helium is not gravitationally bound to the Earth. Thus, unlike other geochemical tracers, it is not available for return to the mantle at subduction zones. Over geologic time, the melt extraction events implicated in planetary differentiation should have stripped $^3$He from the planet

The author is at the Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964.

and, when coupled with $^4$He production from U and Th decay, would be expected to yield very low $^3$He/$^4$He ratios within the mantle.

Low helium isotope ratios have not been observed in mantle-derived rocks, however. Most dramatically, $^3$He/$^4$He ratios many times higher than can be attributed to radioactive decay have been measured in lavas from intraplate volcanos such as the Hawaiian Islands (2–4). Such volcanos are thought to be the surface expressions of mantle plumes, jets of hot material that rise from deep within the mantle. The most obvious candidate for the source of high $^3$He/$^4$He ratios is an "undegassed" reservoir—a portion of the Earth that has retained much of its original $^3$He. Given the strong affinity of helium for melts, a completely undegassed mantle reservoir could survive only if it has been isolated from melt extraction throughout geologic time. Thus, high $^3$He/$^4$He ratios may be the signature of relatively undifferentiated or "primitive" mantle. In addition to providing unique constraints on the Earth's primordial composition, the survival of a primitive reservoir places severe constraints on mantle evolution and dynamics. For example, it precludes theoretical suggestions of whole mantle melting during the late stages of accretion and core formation and argues for layered mantle

convection (Fig. 1). With the possible exception of other rare gases, no other geochemical tracers convey such information.

The assignment of high $^3$He/$^4$He ratios to a primitive mantle reservoir is, however, highly controversial because it is at odds with standard interpretations of other geochemical evidence. For example, basalts with the highest $^3$He/$^4$He ratios do not have Pb isotope ratios consistent with closed-system evolution for the 4.55-billion-year duration of Earth history (5). Although a primitive reservoir cannot be ruled out, an alternative source of high $^3$He/$^4$He ratios has long been sought. The Earth's iron core is one such possibility, but recent experimental work suggests that it is very unlikely that substantial quantities of helium reside there (6). Building on earlier suggestions (7), Anderson now advocates a very different source for mantle $^3$He: subducted extraterrestrial material.

Extraterrestrial (ET) matter is characterized by high helium concentrations and $^3$He/$^4$He ratios many times higher than those observed within the Earth. During atmospheric entry, most ET material fuses and releases its helium, but tiny (diameter typically less than 20 μm) interplanetary dust particles (IDPs) are small enough to escape intense frictional heating. Although IDPs undergo a chemical transformation to magnetite during atmospheric entry, they do so without extensive loss of helium. Accumulation of IDPs on the Earth's surface is readily observable in the helium isotopic composition of the surface layers of very slowly accumulating pelagic sediments, which can have $^3$He/$^4$He ratios hundreds of times higher than purely terrigenous sediments (8). The fate
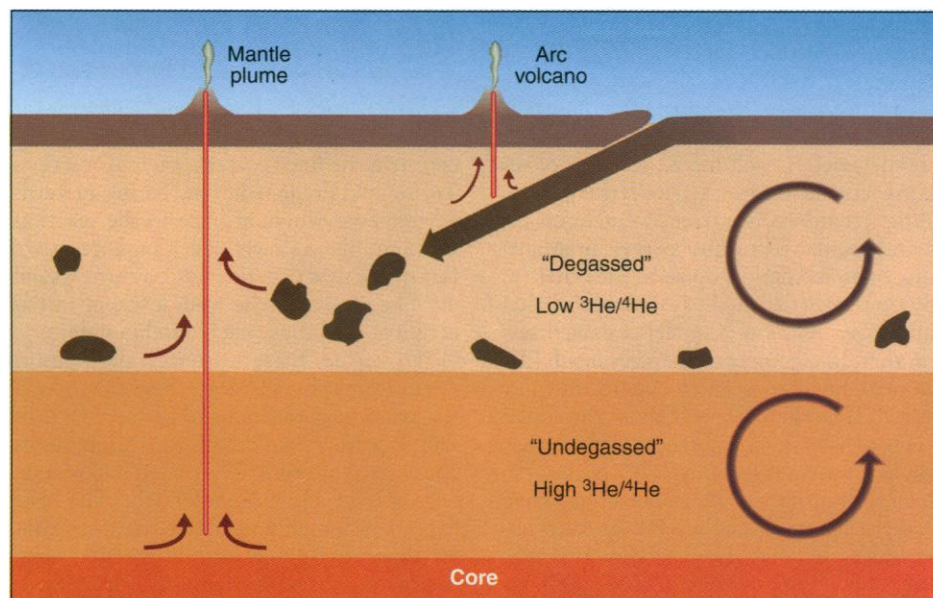


**Fig. 1.** In the traditional view [see, for example (4)], the high $^3$He/$^4$He ratios represent undegassed mantle that has retained primordial $^3$He since accretion. The undegassed reservoir is likely to reside in the lower mantle, and its long-term preservation requires that it be convectively isolated from the degassed upper mantle and also from subducting crustal material (dark blobs). Mantle plumes with high $^3$He/$^4$He ratios are derived from the deep, undegassed source.

of the ET helium in sediment-hosted IDPs is unknown; it may be released to the oceans by diffusive loss or weathering, or as Anderson proposes, it may be injected along with the sedimentary package into the mantle at subduction zones. Anderson argues that subduction is likely because magnetite is chemically stable in oceanic sediments and because helium diffusion from magnetite is apparently quite slow. Thus, subduction of IDP-rich sediments may continuously refertilize the mantle with $^3$He.

If substantial quantities of ET helium are injected into the mantle, high $^3$He/$^4$He ratios may not be the signature of an undegassed or primitive mantle source, but the complete opposite: a unique indicator of subducted sediments. This explanation would not require that primordial $^3$He be retained within the Earth during planetary differentiation and would neatly reconcile the helium data with the large body of evidence supporting the return of crustal material to the mantle. It would also explain why the highest $^3$He/$^4$He ratios occur in mantle plumes, which many workers believe are partially composed of recycled crust. Furthermore, because the IDPs carry ET neon as well as helium, Anderson's hypothesis can simultaneously explain the previously puzzling observation that mantle-derived rocks have $^{20}$Ne/$^{22}$Ne ratios that look more like ET matter than like the atmosphere (7, 9).

Anderson suggests that the $^3$He-rich subducted material is emplaced and stored for long periods in the shallow mantle, from which it may be extracted by ascending melts such as mantle plumes. Alternatively, it could travel deep within the mantle, perhaps all the way to the core, and actually be the source of mantle plumes (Fig. 2).

Although Anderson's hypothesis has great theoretical appeal, several assumptions and observations need to be more fully investigated before the "primordial helium" paradigm is discarded. An important question is whether sufficient ET helium is delivered to the mantle to account for the $^3$He abundances observed in mantle rocks. Two factors affect the injection rate of ET helium into the mantle: the IDP flux and the survivability of the particles on the sea floor. As Anderson acknowledges, even if all the ET helium now falling to the sediments penetrates the subduction zone, it is still orders of magnitude less than the current exhalation rate from the mantle. However, because the recycled crust sampled by plumes may have been returned to the mantle billions of years ago, Anderson argues that a fallout rate greater than today's may have existed at the time of subduction. Although a greater IDP flux earlier in the history of the solar system is plausible, it is very difficult to substantiate.

Furthermore, there is as yet little evidence that IDPs can retain helium for the tens of
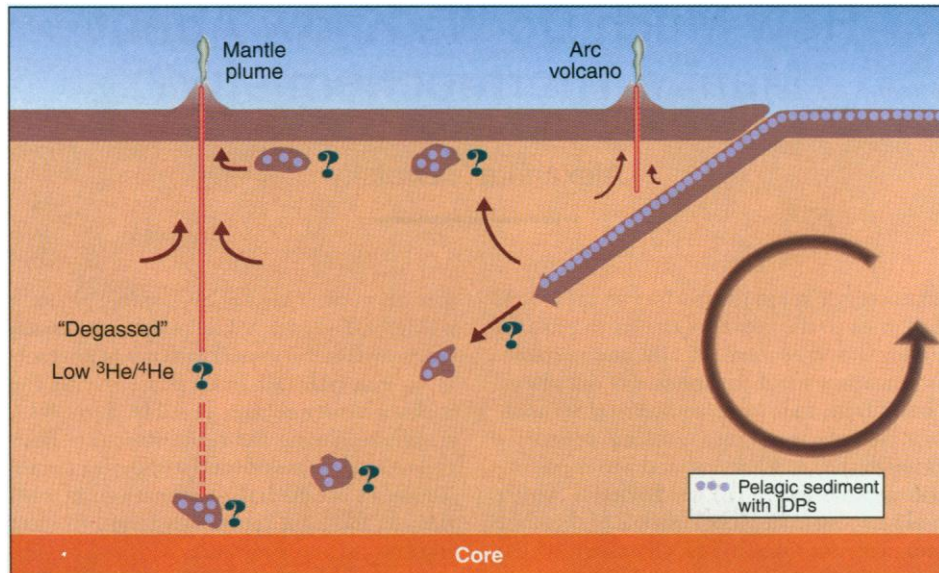


**Fig. 2.** In Anderson's model ( 1), high $^3$He/$^4$He ratios in the mantle are produced by the subduction of $^3$He-rich IPDs. These particles retain ET helium as they migrate to the subduction zone and also as they pass through the zone from which island arc lavas are derived. In Anderson's view, the recycled material is then deposited into the shallow mantle, where it can be swept out by ascending melts such as mantle plumes. Equally plausibly, it may descend deep within the mantle and actually be the source of mantle plumes. In either case, the existence of high $^3$He/$^4$He ratios would not require layered mantle convection.

millions of years between infall and subduction. The only evidence to support long-term retention of helium in magnetite comes from a study of a terrestrial ore (10), which is chemically and mineralogically different from the IDPs. In this regard, it is disturbing that the few very old sediments (up to 70 million years old) that have been analyzed for helium have low $^3$He/$^4$He ratios (6). Although this may be attributed to dilution by terrestrial sediments, it may also result from near complete loss of the ET helium. Whether magnetite is helium-retentive on the sea floor and also at elevated temperatures during passage through the zone of island arc melting can be addressed in a straightforward manner with laboratory experiments.

Perhaps most problematic for the IDP hypothesis is that the highest $^3$He/$^4$He ratios are not found in mantle plumes that have the greatest proportion of recycled crust as inferred, for example, from high $^{87}$Sr/$^{86}$Sr ratios (5, 11). Anderson argues that this can be explained by the composition of the subducted sediments: slowly accumulating sediments with a high proportion of IDPs would be favored during periods of slow continental erosion and hence low sea water (and sediment) $^{87}$Sr/$^{86}$Sr ratios. This signature of high $^3$He/$^4$He and low $^{87}$Sr/$^{86}$Sr would then be preserved within the mantle. However, postsubduction radioactive decay of $^{87}$Rb must also be considered. A mixture of 5% pelagic sediments subducted 2 billion years ago with 95% ambient depleted mantle, as Anderson proposes for plume basalts, would probably have an $^{87}$Sr/$^{86}$Sr ratio in excess of 0.706 today. This is in contrast to values <0.7045 mea-

sured in most basalts with high $^3$He/$^4$He ratios. Although this discrepancy can be alleviated by the assumption of an arbitrarily small fraction of sediment in the plume basalts with a correspondingly larger IDP content, such an assumption is clearly ad hoc and demonstrates that the model requires further observational constraints.

Anderson has made a strong case that $^3$He measured in mantle-derived rocks should not in all cases be considered of primordial origin, but the extent to which subducted IDPs can account for the high $^3$He/$^4$He ratios in the mantle requires further investigation. Laboratory studies of the long-term retentivity of rare gases in ET magnetite in relevant geochemical environments and more detailed studies of the relationships between lithophile isotopic tracers and helium in mantle materials are clearly required. In addition, the last few years have seen rapid advances in the analysis of the heavier rare gases, which will soon provide new insights to the origin of mantle $^3$He.

**References**

1. D. L. Anderson, *Science* **261**, 170 (1993).
2. W. Rison and H. Craig, *Earth Planet. Sci. Lett.* **66**, 407 (1983).
3. M. D. Kurz et al., *ibid.*, p. 388.
4. C. J. Allegre et al., *Nature* **303**, 762 (1983).
5. K. A. Farley, J. H. Natland, H. Craig, *Earth Planet. Sci. Lett.* **111**, 183 (1992).
6. J. Masuda et al., *Science* **259**, 788 (1993).
7. P. Sarda, T. Staudacher, C. J. Allegre, *Earth Planet. Sci. Lett.* **91**, 73 (1988).
8. M. Ozima et al., *Nature* **311**, 449 (1984).
9. M. Honda et al., *ibid.* **349**, 149 (1991).
10. F. P. Fanale and J. L. Kulp, *Econ. Geol.* **57**, 735 (1962).
11. S. R. Hart et al., *Science* **256**, 517 (1992).