Helium Loss, Tectonics, and the Terrestrial Heat Budget

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It has been known for the last decade that primordial helium incorporated in Earth at the time of its formation is still being degassed during the formation of new ocean crust at spreading ocean ridges. It is now clear that somewhat contrary to expectation, substantial degassing is also taking place through the continental crust. In western Europe the escape of mantle volatiles seems to occur largely where the crust is undergoing active extension. Although it is known that melting is the principal process for extracting and concentrating helium from the mantle at ocean ridges, the equivalent subcontinental process remains poorly understood. The same elements that are responsible for most of Earth's radiogenic heating (uranium and thorium) are also responsible for the generation of radiogenic helium. The present rate of mantle heat loss, however, is out of equilibrium with the rate of helium loss—too large by about a factor of 20. Either radiogenic helium is accumulated in the mantle while heat escapes or current models for the bulk chemistry of Earth are in error and much of the terrestrial heat loss is nonradiogenic.

HELIUM, THE SECOND MOST ABUNDANT ELEMENT IN THE solar system, was excluded from the terrestrial planets at the time of their formation. The helium/silicon ratio of Earth, for example, is 12 or more orders of magnitude lower than that of the primordial solar nebula, and the rare gases in general are present at only trace levels in the terrestrial planets. In contrast thorium and uranium, the principal sources of radiogenic ^{4}He, were incorporated into the terrestrial planets without significant fractionation from silicon, with the result that radiogenic helium is relatively more abundant than primordial helium in Earth than in the solar system as a whole. This gives rise to the present situation where radiogenic helium predominates over primordial helium in Earth. Fortunately, the ^{3}He/^{4}He ratio of primordial helium is about four orders of magnitude larger than is typical for radiogenic helium, which allows the primordial helium component to be recognized even when it is present at a level of only 1% or less. It is these properties of helium that have made it possible to demonstrate that Earth is still degassing primordial helium at spreading ridge axes at a measurable rate, and to use helium as a powerful tracer of mantle-derived fluids in the continents (*1*).

The isotopes ^{235}U, ^{238}U, ^{232}Th, and ^{40}K are both the principal sources of radiogenic heat in Earth and the parent isotopes of radiogenic helium and argon (*2*). As a consequence, radiogenic heat and rare gas production in Earth are coupled in both space and time. At present, approximately 10^{12} atoms of ^{4}He and 2×10^{11} atoms of ^{40}Ar are produced per joule of heat for bulk Earth potassium/uranium and thorium/uranium ratios of 1.3×10^4 and 3.8×10^4, respectively. This relation is expected to be typical of the continental crust, which has potassium/uranium and thorium/uranium ratios close to the bulk Earth values. The production ratio is only marginally lower in the upper mantle, which has thorium/uranium $\approx$2.5 (*3*). The generation of some other rare-gas isotopes is also related to radiogenic heat production—these isotopes include ^{136}Xe produced by spontaneous fission of ^{238}U; ^{21}Ne and ^{22}Ne produced by (α,n) reactions on ^{18}O and ^{19}F, respectively; and ^{3}He that arises through the capture of neutrons, which are produced by reactions such as those above, by ^{6}Li(n,α)^{3}H $\rightarrow$ ^{3}He (*4*). In the latter case the required neutron flux arises from ^{238}U spontaneous fission and a variety of (α,n) reactions that depend on rock chemistry. Of these, the radiogenic production rate of ^{3}He relative to ^{4}He is particularly relevant to the present discussion. The results of calculations by several investigators, coupled with observations in natural systems, suggest that the ^{3}He/^{4}He production ratio will be $\leq 5 \times 10^{-8}$ for typical mantle and crustal rock compositions (*5, 6*). If possible contributions to the ^{3}He budget from bomb-produced tritium are neglected for the present, then terrestrial ^{3}He/^{4}He ratios exceeding $\sim 5 \times 10^{-8}$ arise either from generation of radiogenic helium in rock compositions with exceptionally high lithium content or from an admixture of primordial helium to normal radiogenic helium. In general, the helium from the decay of bomb-produced tritium, which has been exploited so successfully as a tracer in the oceans and young ground waters, makes a negligible contribution to the samples described below and will not be discussed further.

Because helium is not retained by the atmosphere, its atmospheric abundance is very low (about 5 ppm). Its isotopic composition is in part controlled by the bulk composition of helium being degassed from Earth's surface, in part by the different atmospheric residence times of the two isotopes, and in part by the composition of the small amount of helium produced by cosmogenic spallation reactions and auroral precipitation (*7*). This article is primarily concerned with the distribution of radiogenic and primordial helium isotopes in Earth's crust and their tectonic significance. Although in principle it is possible to exploit the isotopic compositions of the heavier rare gases in an analogous manner, the much smaller differences in the isotopic compositions of their radiogenic and primordial components, together with their relatively high abundances in the atmosphere and hydrosphere, make them significantly less useful for this purpose.

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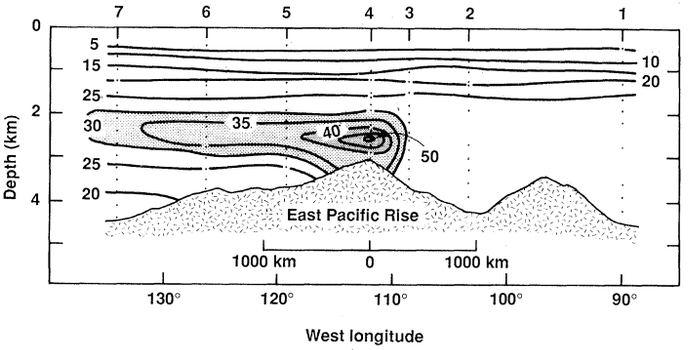

Fig. 1. Escape of helium by hydrothermal stripping at a spreading ridge axis. The diagram shows the distribution of ^{3}He anomalies at 15°S across the East Pacific Rise, after Lupton and Craig (*10*). The source of ^{3}He centered upon the ridge axis owes its origin to hydrothermal stripping of helium from new oceanic crust. Contour lines show $\delta(^3\text{He})$, the percentage deviation of measured $^3\text{He}/^4\text{He}$ ratios at each sampling station (numbered along top) from the $^3\text{He}/^4\text{He}$ ratio of atmospheric helium.

Loss of Volatiles from the Crust

Oceanic crust. Clarke and others (*8*) demonstrated from ^{3}He anomalies in the deep ocean that primordial helium is still degassing from Earth's interior. The subsequent observation that $^3\text{He}/^4\text{He}$ ratios in both ocean-ridge basalt glasses and associated high-temperature hydrothermal vent fluids (*9, 10*) substantially exceed the atmospheric ratio not only confirmed the presence of primordial helium in the mantle but suggested that it makes up about 10% of the total helium. The degassing of helium along the East Pacific Rise and its dispersal into the Pacific Ocean is illustrated spectacularly by Lupton and Craig's (*10*) mapping of ^{3}He saturation anomalies (Fig. 1). When the estimate of global ^{3}He excess in the oceans is coupled with that of the ventilation rate, an estimate can be made of the ^{3}He flux from the mantle through the ocean basins of $4 \times 10^4 \pm 1 \times 10^4$ atoms per square meter per second (*11*). This estimate does not include ^{3}He lost subaerially from volcanic islands in the ocean basins, but, given that about 80% of the oceanic volcanism occurs along spreading ridges, this omission is unlikely to affect the estimate greatly.

The helium released to the oceans at ridges is about eight times as rich in ^{3}He as the atmosphere ($R/R_a = 8$, where R is the measured value of $^3\text{He}/^4\text{He}$ and R_a is the ratio measured in air) and this composition is reasonable for primordial helium that has been diluted with ~90% radiogenic helium during its long residence in the mantle (*12*). During sea-floor spreading new oceanic crust is generated at about 3 km^2 year^{-1} (*13*), corresponding to some 20 km^3 year^{-1} of new basalt. This represents a partial melt from underlying mantle material that appears to have been quantitatively stripped of mantle helium principally by the hydrothermal circulation at ridges. To a first approximation the helium flux and the rate of creation of new oceanic crust may be related to give 53 moles of ^{3}He per cubic kilometer of basalt. It is much less straightforward to estimate the volume of mantle effectively degassed by this processing. The major element chemistry of oceanic basalts requires that about 10 to 15% of the mantle source melts, but there are indications that highly incompatible trace elements such as thorium may be contributed by very small (<1%) melt fractions from larger mantle volumes (*14*). The distribution coefficients of the rare gases between melts and residual mantle are inadequately known from direct laboratory experiments (*15*), but there is indirect evidence to suggest that helium is highly incompatible and behaves like elements such as thorium. For example, helium has an approximately thousandfold lower abundance in crystalline basalts, olivine phenocrysts, and ultramafic xenoliths than submarine basaltic glasses. Similarly, CO_2, with which helium is commonly associated, fractionates very strongly into the melt phase rather than the residual solids.

The measurement of a contemporary ^{3}He degassing flux from the oceanic crust is an important development because it provides a basis both for placing limits on the chemical fluxes of other species and for a comparison of present radiogenic helium and heat fluxes. However, these rates may have been different in the past. Because helium, unlike the heavier rare gases, is not conserved, the present flux cannot be compared with an accumulated "atmosphere" inventory. However, the evidence from argon and xenon isotope abundances suggests that their degassing rate would have been at a maximum in the first few hundred million years of Earth history. It is reasonable to assume that the same is true of helium.

The fluxes of major volatile species from the mantle such as carbon are less well constrained than those of the rare gases. A promising approach to the problem derives from the observation (*16*) that C/^{3}He ratios in mid-ocean ridge basalts and high-temperature vents average 10^9 with only about one order of magnitude total variation. The carbon degassing flux derived from this ratio and the ^{3}He flux deduced above (that is, $\sim 10^{13}$ atoms per square meter per second) is probably the best currently available.

Continental crust. The continental crust contains a significant fraction of Earth's uranium and thorium, possibly as much as 50%, and this is highly concentrated in the uppermost 10 km or so. It is not surprising therefore that natural gases and ground waters often contain high abundances of radiogenic helium. It has been known for some time that primordial helium too may occur locally at shallow levels within the continents, particularly in association with high-enthalpy geothermal systems such as those at Yellowstone, Geysers, Steamboat Springs, and Larderello (*17*). However, the compilations made by Mamyrin and Tolstikhin (*6, 18*), for example, demonstrate that only rarely in continental environments does mantle-derived helium dominate over crustally generated radiogenic helium.

If it is assumed that the rate of loss of radiogenic helium from the continents equals its rate of production, then following O'Nions and Oxburgh (*19*) the steady-state radiogenic flux would be 2.8×10^{10} atoms per square meter per second. If a flux of helium from the mantle to the continental crust occurred at the same rate as over the oceans (5×10^9 atoms per square meter per second and $R/R_a = 8$), the combination of this flux with the continental radiogenic flux would produce a mixture with an average $^3\text{He}/^4\text{He}$ value of 1.8×10^{-6}. Results obtained in Cambridge and elsewhere (Fig. 2) on the distribution of helium isotopes in western Europe reveal areas with helium having substantially higher and lower ratios. In the crust and continental shelf of the United Kingdom, for example, $^3\text{He}/^4\text{He}$ ratios are uniform and very close to the estimated radiogenic production ratio ($\leq 5 \times 10^{-8}$); elsewhere, such as in the Pannonian Basin, the southern Rheingraben, and Massif Central, $^3\text{He}/^4\text{He}$ ratios exceed this value and in certain areas where there is active volcanic activity approach ratios typical of mantle helium (Fig. 3). There are several possible explanations for the very low $^3\text{He}/^4\text{He}$ ratios found in many continental areas. Either the mantle helium flux through much of the continents is one to two orders of magnitude lower than through the ocean basins, or crustal radioactivity is much higher in some areas than expected, or departures from steady-state helium degassing are extreme. Conversely, in those areas where mantle helium is identifiable in the continental crust, then either crustal radioactivity is anomalously low or the mantle helium flux is greater than the average value. These possibilities obviously cannot be evaluated on the basis of helium isotope measurements alone, but it will be shown below that considerations arising from regional heat-flow patterns eliminate the possibility

that these variations arise solely from the distribution of radioactivity within the crust.

Whereas a steady-state relation between radiogenic helium production and loss for the continents is often assumed, it is in fact difficult to prove because no generally established method of measuring continental helium flux has been devised. Where estimates are available from accumulated helium budgets of small lakes (*20*), they appear to be highly variable. On a regional scale the study of helium distribution as a function of ground-water age in the Great Artesian Basin of Australia by Torgersen and Clarke (*21*) provides some insight into crustal degassing. These researchers demonstrated that the accumulation of radiogenic helium in ground water far exceeds that which could be generated within the Basin aquifers themselves, and conclude that degassing of the entire radiogenic helium complement of the crust is required to sustain the observed relations. In addition to diffusive fluxes and hydrological scavenging of helium, there must also be a significant loss of crustal helium by simple erosion processes in areas of rapid uplift and erosion. There is a need for additional studies of this kind that effectively provide insight into the integrated degassing behavior of the continents on a regional scale; the available data are, however, consistent with a loss of helium from the continents that is in a steady state if viewed over tens of millions of years but that may fluctuate on a shorter or much longer time scale.

Details of the distribution of mantle-derived helium in the continents are therefore primarily related to changes in magnitude of the mantle helium flux. Consideration of the distribution of ^3He in the crust of western Europe (Figs. 2 and 3) reveals a number of features, some of which are surprising in view of the tectonic settings.

1) The United Kingdom mainland and shelf are an area of some 10^6 km^2 over which mantle helium components are $\leq 0.5\%$ of the total helium present and radiogenic sources are entirely dominant. This part of Europe, which is characterized by stable tectonic conditions, serves as a convenient reference standard for western Europe.

2) Primordial helium is absent or present in very low concentrations in the inactive central graben of the North Sea but is present in the seismically active southern portion of the Rheingraben (*22*). Away from the boundary faults of the graben, which probably serve as conduits for mantle helium, the mantle component rapidly becomes undetectable.

3) In one area that appears to be seismically quiet, has low heat flow, and shows no sign of recent tectonic activity, there is,

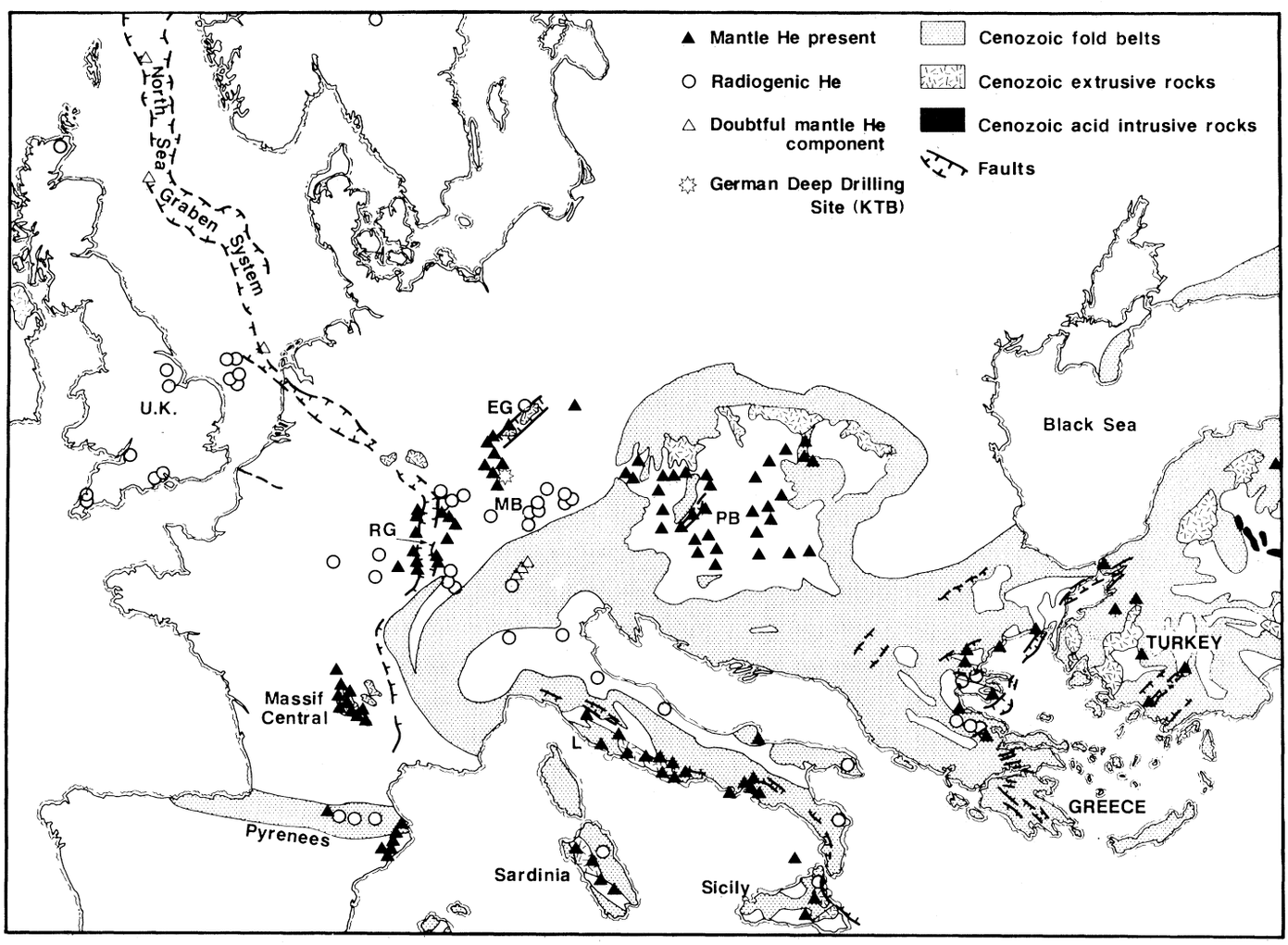

Fig. 2. Distribution of helium isotopes in the crust of western Europe. Samples are only distinguished on the basis of whether or not a mantle-derived primordial component can be identified. All samples with $R/R_a > 0.08$ (*12*) are interpreted as containing a mantle component in addition to the radiogenic helium generated in the crust. Open triangles indicate samples just above this limit that may contain ~0.5% mantle helium or may be radiogenic but derived from unusually lithium-rich source rocks. [Data from *21–23, 32, 33*, and unpublished.] Abbreviations: The star indicates the location of the German deep drilling site (KTB) in the Oberpfalz. Other locations are MB, Molasse Basin; PB, Pannonian Basin; RG, Rheingraben; EG, Egergraben.

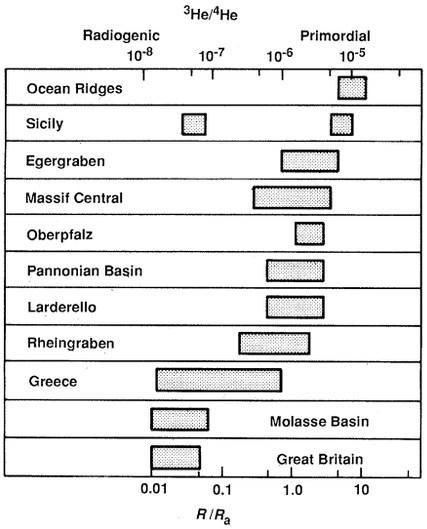

Fig. 3. Ranges of $^3He/^4He$ and corresponding R/R_a values (*12*) for ocean ridges and various localities in western Europe (see Fig. 2). Radiogenic helium typically has $^3He/^4He \leq 5 \times 10^{-8}$ and this is characteristic of the United Kingdom crust and shelf. Mantle helium as observed in spreading ridges (Fig. 1) has $^3He/^4He \approx 1.2 \times 10^{-5}$, and a component from this source is evident in the helium sampled from each of the other areas. [Data sources as for Fig. 2.]

surprisingly, a very strong mantle signature ($R/R_a \leq 2.9$). This is the Oberpfalz (West Germany) where super-deep continental drilling (KTB) is shortly to begin. The reason for this helium signature is not yet clear but it may be that the drilling will provide some surprises.

4) There is a clear mantle signature in the helium associated with every region of young volcanic activity.

5) The majority of ground-water samples from areas of contemporary active extension in western Turkey and Greece contain detectable mantle helium and there are close relationships between fluid circulation and the active east-west normal faults.

6) Mantle helium has been identified in all samples studied from the Neogene Pannonian Basin, which is presumed to have developed as an extensional basin, but not in the Molasse or Po basins which are loading basins of similar age (*23*).

A clear relation exists in western Europe between areas of active extension, such as the Aegean and southern Rheingraben, and the presence of mantle-derived ^3He anomalies. However, a few other areas, such as the Oberpfalz, show similar anomalies that are at present unexplained.

The Global System: Helium and Heat Flow

The mantle. The fluxes of helium and heat from the mantle are known reasonably well in oceanic areas; the heat flux averages about 100 mW m^{-2} (*24*) and the ^4He flux is unlikely to much exceed the value of Craig *et al.*, 4×10^9 atoms per square meter per second (*11*). O'Nions and Oxburgh (*19*) have used these values to show that the uranium and thorium required to support the radiogenic component of the mantle helium flux, when combined with the amount of potassium derived from the potassium/uranium ratio $\approx 10^4$, would support only a small fraction of the observed heat flux. The observed ^4He/heat ratio is 4×10^{10} atoms per joule (as compared to the expected production ratio of about 10^{12}). This large imbalance between the heat and helium fluxes is far outside the uncertainties assigned and suggests that the measured helium flux for the mantle accounts for only about 5% of the heat flow. The distribution of the uranium and thorium that supports the radiogenic helium flux is not constrained, but its mean concentration would amount to approximately 5 ppb of uranium and equivalent thorium, if confined to the upper mantle. In principle, there should be a similar imbalance for radiogenic ^{40}Ar, and the degassing flux ratio of helium to argon should be equal to the time-integrated radiogenic production ratio, which lies between 2 and 3. Direct measurements of the ^{40}Ar flux, however, are hampered by the high concentration of ^{40}Ar (1%) in the atmosphere and surface environment. The measured $^4He/^{40}Ar$ ratios of spreading ridge axis basalt glasses range from approximately 1 to 20 (*25*), and generally exceed the production ratio. However, this range must be strongly influenced by the differential solubilities of helium and argon in silicate melts (*26*), and at this stage the available data for argon are not in conflict with the conclusions drawn from helium and heat flux considerations.

A similar mismatch of the helium flux is indicated by most recent estimates of Earth's uranium content. These place it close to 20 ppb for the crust and mantle as a whole (*27*), which suggests that the measured radiogenic helium flux from the mantle accounts for only about 10% of the helium produced. The present measured oceanic heat flow is believed to be higher than that supported by present-day, whole-Earth radioactivity. This difference, however, is not more than a factor of 2, and in any case has little effect on the problem unless it is envisaged that heat and helium can move independently of each other over long distances in the mantle and at different rates (*19*).

This paradox can, however, be resolved if at some depth within the mantle there is a boundary across which the diffusivity of heat is greater than that for helium, but at the same time low enough to impose a thermal time constant of about 2.0×10^9 years on heat loss from the planet as a whole (*28, 29*). This explanation is by no means unique, but other possibilities such as a nonradiogenic core source for a large portion of the heat flux imply that bulk Earth uranium estimates are too high; another possibility is that helium is incompletely removed from the mantle during partial melting and crust formation at mid-ocean ridges. This, however, would require that helium behaves as a relatively compatible element contrary to the expectations expressed above and would be inconsistent with recent experimental evidence (*15*).

The continents. A comparison of helium and heat fluxes from the continents, such as that made above for the ocean basins, is made difficult by the lack of direct continental helium flux measurements. However, on the basis of $^3He/^4He$ ratios in crustal fluids and regional heat flow, Polyak and co-workers (*30*) have claimed a linear relation between regional heat flow (q) and $\log(^3He/^4He)$, which they consider to be a fundamental characteristic of the crust. In general terms a relation of this kind might be anticipated simply because the spreading ridges are characterized by both high heat flow and high $^3He/^4He$ ratios, whereas the radiogenic helium characteristics of stable cratonic regions are usually accompanied by low heat flow values (*24*). In detail, however, this proposed linear relation does not hold for the crust of western Europe. Heat flow values in the United Kingdom range from 50 to 125 mW m^{-2} with a uniform $^3He/^4He \sim 5 \times 10^{-8}$. For such a range of heat flow values the relation of Polyak *et al.* would predict a change in $^3He/^4He$ from 10^{-5} to 10^{-7}.

The relations between $^3He/^4He$ ratios and continental heat flow may be pursued through a consideration of the empirical Birch Law (*31*), which relates surface heat flow and measured crustal radioactivity, by

$$q = q_m + Ah$$

where q is the conductive surface heat flow, A is the heat production in near surface rocks, h is a characteristic length scale, and q_m is the intercept heat flow value for zero heat production. Formally q_m is the heat flow conducted from beneath the layer containing the radioactivity; but it is often simply interpreted as the heat flow conducted from the mantle. If the helium flux is similarly considered as comprising two components, a mantle-derived flux j_m and a continent-derived radiogenic flux j_c (each having different isotopic compositions), then for fixed values of q_m and j_m/q_m, the $^3He/^4He$

ratio at the surface will decrease with increasing q, as long as crustal radioactivity remains an important source of both heat and ^{4}He (that is, j_c/Ah remains constant). Conversely, if j_m increases while j_m/q_m and Ah remain fixed, ^{3}He/^{4}He will increase with increasing q. If both variations occur in nature, as seems intuitively reasonable, then no simple linear relation between q and ^{3}He/^{4}He can exist, and the wide variations of ^{3}He/^{4}He at constant q exhibited by the data of Polyak *et al.* are to be expected. Indeed there is abundant evidence that q_m does vary and may be several times as high in young, tectonically active terrains, as in older cratons (*24*).

It is possible to place some limits on the value of j_m/q_m at least for the heat and helium fluxes in the ocean basins. The helium/heat flux ratio in the ocean basins is 4×10^{10} atoms per joule, and the corresponding value for j_m/q_m required to satisfy both the q_m values derived for cratonic regions, which are typically between 25 and 35 mW m^{-2}, and the ^{3}He/^{4}He ratios close to 10^{-8}, is at least an order of magnitude lower than the oceanic ratio at $\leq 5 \times 10^9$ atoms per joule.

In some other continental areas such as the southern Rheingraben and Pannonian Basin where q_m is perhaps not more than 50% higher than the cratonic values, the j_m/q_m ratio must be higher by at least a factor of 10 than for the cratons, assuming that departures from steady-state behavior are of secondary importance. Taken together, these simple considerations point to a major and variable decoupling of heat and helium in the continental lithosphere, which must relate to the mechanisms involved in the transport of helium and heat. In regions where heat is conducted and helium travels by diffusion, such as probably occurs through the deep parts of the old stable cratons, then the thermal diffusivity must be greater than the helium chemical diffusivity. The presence of mantle helium in other continental areas, however, points to advective transport of helium into the crust, most probably associated with silicate melts and their degassing products. In these situations it is conceivable that degassed mantle helium may be observed at the surface even though conduction remains the dominant mechanism for heat transport.

Transport of helium and heat. To a large extent the systematics of the relation between the fluxes of helium and heat depend on transport processes. From what has been said earlier it is clear that partial melting allows the efficient extraction of helium, and movement of magma is effective at transporting both heat and helium. It is also clear that the movement of other fluids such as ground water will remove and advect both heat and helium from rocks through which they can circulate. This is a crustal process and will lead to a coupling between radiogenic heat and radiogenic helium. In the absence of either of these fluid processes helium and heat will both be transported advectively by large-scale solid-state convection processes or diffusively by lattice conduction and chemical diffusion. At relatively low pressures and temperatures (those of the upper crust) heat seems to diffuse more rapidly than helium through silicate materials. The experimental observations on helium are, however, very limited. It is possible that this difference is much enhanced at greater mantle depths, with relatively little chemical diffusive transport occurring in dense mantle phases.

Conclusions

In many areas the continents seem to behave as nearly impermeable lids through which there is no detectable loss of mantle volatiles from the underlying mantle. Where continents are undergoing active extension with normal faulting in their upper parts, and where there is young volcanic activity, the seal is broken and mantle-derived fluids are clearly present in the near-surface environment. It may be that mantle gases are the early precursors of crustal tectonic and thermal events, and this may be the case at the German deep-drilling site.

Regardless of the processes that may operate within and under the continents, the helium flux to the deep oceans establishes without doubt that Earth still retains primordial helium incorporated at the time of formation; if helium is retained, it is certain that other gaseous species such as nitrogen, argon, and neon are retained as well.

The helium flux to the oceans, however, contains a radiogenic component that is only 5% of that expected from radioactivity sufficient to support the present oceanic heat flow. Either radiogenic helium is being retained deep within Earth, or present models for the chemical and thermal evolution of Earth are seriously in error.

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Biomaterial-Centered Infection: Microbial Adhesion Versus Tissue Integration

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Biomaterials are being used with increasing frequency for tissue substitution. Complex devices such as total joint replacements and the total artificial heart represent combinations of polymers and metal alloys for system and organ replacement. The major barriers to the extended use of these devices are the possibility of bacterial adhesion to biomaterials, which causes biomaterial-centered infection, and the lack of successful tissue integration or compatibility with biomaterial surfaces. Interactions of biomaterials with bacteria and tissue cells are directed not only by specific receptors and outer membrane molecules on the cell surface, but also by the atomic geometry and electronic state of the biomaterial surface. An understanding of these mechanisms is important to all fields of medicine and is derived from and relevant to studies in microbiology, biochemistry, and physics. Modifications to biomaterial surfaces at an atomic level will allow the programming of cell-to-substratum events, thereby diminishing infection by enhancing tissue compatibility or integration, or by directly inhibiting bacterial adhesion.

THE TWO MAIN BARRIERS TO THE EXTENDED USE OF IMplanted biomaterials and complex artificial organ devices are the possibility of biomaterial-centered infection and the lack of successful tissue integration of biomaterial surfaces. These seemingly disparate phenomena are actually similar expressions of cell-to-substratum surface interactions. "Foreign body" (biomaterial)–centered infections are causally related to the highly adaptive ability of bacteria to colonize the surfaces of "inert" biomaterials or of adjacent, damaged tissue cells (*1–9*). Successful tissue integration of biomaterials depends on the ability of tissue cells to arrive at an intimate, possibly chemically bonded relation between their membrane molecular entities and the biomaterial surface (*6, 10, 11*).

Interactions between bacteria or tissue cells and a substratum surface depend largely on the surface and near-surface atomic structure and composition of implanted biomaterials (*6, 10, 12*). This article reviews recent studies in the composite science of cells and surfaces and outlines the significance of and relation between microbial colonization of biomaterials and tissue cell integration of those surfaces in the "race for the surface."

It is suggested that the fate of an available surface may be conceptualized as a race for the surface, which is a contest between tissue cell integration and bacterial adhesion to that same surface. Host defense systems that are perturbed by biomaterials are a vital factor. If the race is won by tissue, then the surface is occupied and defended and is thus less available for bacterial colonization.

Numerous biomaterial components are permanently or temporarily implanted in humans, including the artificial heart, joint replacements, contact lenses, heart valves, vascular prostheses, dental implants, fabrics and sutures, and intravascular catheters. Ultimately, almost every human in technologically advanced societies will host a biomaterial. Resistant, recurrent, often catastrophic, and always costly infection is a frequent complication of the use of these materials. Infection of a vascular or total joint prosthesis will almost always result in reoperation, osteomyelitis, amputation, or death. Combined rates of death or amputation from infected cardiac, abdominal, and extremity vascular prostheses may exceed 30% (*13–15*). Transcutaneous or transmucosal devices such as intravenous catheters, peritoneal dialysis catheters, and urologic devices rarely escape infection if left indwelling for any length of time (*13, 14*).

Pathogenic Sequence in Substratum-Induced Infection

When nonliving substrata (the artificial heart, biomaterial implants, and some tissue transplants) are introduced into mammalian hosts, they may become favored sites for adhesive bacterial colonization, especially in the immunocompromised host. Adhesion-mediated infections develop that are notoriously resistant to antibiotics and host defenses and that tend to persist until the biomaterial or foreign body is removed (*4, 5, 8, 15*). The pathogenesis of adherent infections is related, in part, to preferential colonization of inert substrata whose surfaces are not integrated with healthy tissues composed of living cells and intact extracellular polymers (*5, 7, 16–19*).

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