LETTERS

# Helium isotopic evidence for episodic mantle melting and crustal growth

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**The timing of formation of the Earth's continental crust is the subject of a long-standing debate[1,2], with models ranging from early formation with little subsequent growth, to pulsed growth, to steadily increasing growth. But most models do agree that the continental crust was extracted from the mantle by partial melting[3]. If so, such crustal extraction should have left a chemical fingerprint in the isotopic composition of the mantle. The subduction of oceanic crust and subsequent convective mixing, however, seems to have largely erased this record in most mantle isotopic systems (for example, strontium, neodymium and lead). In contrast, helium is not recycled into the mantle because it is volatile and degasses from erupted oceanic basalts. Therefore helium isotopes may potentially preserve a clearer record of mantle depletion than recycled isotopes. Here I show that the spectrum of $^4He/^3He$ ratios in ocean island basalts appears to preserve the mantle's depletion history, correlating closely with the ages of proposed continental growth pulses[4,5]. The correlation independently predicts both the dominant $^4He/^3He$ peak found in modern mid-ocean-ridge basalts, as well as estimates of the initial $^4He/^3He$ ratio of the Earth[6]. The correspondence between the ages of mantle depletion events and pulses of crustal production implies that the formation of the continental crust was indeed episodic and punctuated by large, potentially global, melting events. The proposed helium isotopic evolution model does not require a primitive, undegassed mantle reservoir, and therefore is consistent with whole mantle convection.**

In the most widely cited He evolution models, the $^4He/^3He$ ratios observed in mid-ocean-ridge basalts (MORB) and ocean island basalts (OIB) are interpreted in terms of mixing between two reservoirs[7–10]. OIB are thought to sample an undegassed, low-$^4He/^3He$ mantle that has retained most of its $^3He$ since the origin of the Earth and is often associated with the lower mantle. MORB are thought to sample a degassed, high-$^4He/^3He$ mantle that has lost essentially all of its $^3He$ through melting[8,9,11] and is typically associated with the upper mantle. To maintain these two distinct reservoirs requires that they be chemically and physically isolated[7,11], and strongly implies some form of layered mantle convection, though alternative models can be envisaged[10].

However, this model rests upon the assumption that the lowest $^4He/^3He$ values found in OIB are representative of an undegassed mantle component, or at least place upper bounds on its value. This assumption is only valid if the partition coefficient for He ($D^{He}$, where $D^{He} = He_{crystal}/He_{melt}$) is lower than the partition coefficient for its parent isotopes, U and Th ($D^{U+Th}$). Recent experimental data suggest that $D^{He}$ is in fact greater than $D^{U+Th}$ (refs 12, 13). In this case, the mantle residues of melting ('depleted mantle') can preserve low $^4He/^3He$ ratios. Consistent with this, recent studies suggest that OIB and flood basalts with the lowest $^4He/^3He$ have depleted Sr, Nd and Pb isotopic compositions[14,15]. If this is so, then one cannot a priori assume that the lowest-$^4He/^3He$ magmas are representative of an undegassed mantle, and in fact, there would be no requirement for undegassed mantle in the $^4He/^3He$ data.

Even though the experimental partitioning studies are ongoing and incomplete, there is enough evidence for high $D^{He}$ at present for its potential consequences for He isotopic evolution models to be seriously considered. A fundamental difference from existing models is that if $D^{He}$ is greater than $D^{U+Th}$, then the $^4He/^3He$ ratios in OIB could be interpreted in terms of an age of mantle melt depletion[16,17], rather than mixing between degassed and undegassed mantle reservoirs. This age would record the time of melting when U and Th were removed from the mantle residue to a greater extent than He, leaving it with a low (U+Th)/He (parent/daughter) ratio. It is essentially a U–Th depletion age. If $D^{He}$ is more than about 5 times greater than $D^{U+Th}$, then the production of $^4He$ in the residue would effectively cease in the depleted residue and its $^4He/^3He$ ratio would remain constant thereafter.

MORB and OIB provide the primary constraints on the He isotopic composition of the present mantle. MORB generally have higher $^4He/^3He$ ratios than OIB (Fig. 1), with a dominant peak at $(90 \pm 1) \times 10^3$ (in terms of $^3He/^4He$, a ratio of 7.9 $R_a$; $R_a$ is the $^3He/^4He$ ratio of the atmosphere). There are peaks in the OIB data, but the importance of these has generally been downplayed. This is because a few islands (Hawaii, Iceland and Reunion) have a disproportionately large number of analyses relative to their actual volumes, and so they artificially dominate any data compilation. Even within single island groups, specific locations, such as Loihi seamount in Hawaii, are over-sampled with respect to their volume. However, a close inspection of the OIB data reveals that, when island groups are compared on an individual basis, there are certain $^4He/^3He$ peaks that recur in widely separated island groups (Fig. 1, Supplementary Fig. 1).

For most islands, there are only sufficient data to establish the existence of a few statistically significant peaks. However, Hawaii and Iceland both have over 400 analyses each, and so their $^4He/^3He$ spectrum can be resolved in greater detail. Most of their $^4He/^3He$ values lie in the range $(20–70) \times 10^3$. In this range, both islands have eight $^4He/^3He$ peaks and the positions of these peaks match quite well (Fig. 1). Other island groups show these same peaks, though any individual island group only contains a subset of them. In some cases, (Samoa, Kerguelen, Galapagos; see Supplementary Fig. 1), this may largely be due to lack of data, as their $^4He/^3He$ values roughly span the same range as Hawaii and Iceland. Some islands (Reunion, Azores, Canaries) clearly have a lower range of $^4He/^3He$ and fewer peaks. Above values of $70 \times 10^3$, the correlation between Hawaii, Iceland and other OIB largely ceases until the peak at $85 \times 10^3$.

This same gap, $(70–85) \times 10^3$, as well as the peaks at $50 \times 10^3$ and higher, can also be seen in the MORB data. The presence of the $^4He/^3He$ peaks at values below $90 \times 10^3$ in MORB are probably

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due to the influence of nearby plumes (the data plotted have not been filtered in any way). Plume-influenced ridges are generally shallow, and so can be filtered out of the data set by only considering MORB dredged from deep ridges (>3.5 km). When this is done, only data above $75 \times 10^3$ remain (Fig. 1). Thus the peaks in the MORB distribution lower than $75 \times 10^3$ could be transferred to the OIB distribution, but it would not change their position. If the $^4He/^3He$ peaks were purely due to over-sampling, then it is highly improbable that the same peaks would appear on different islands widely separated in distance. This suggests that whereas the relative heights of the peaks may largely be controlled by sampling choices and are not necessarily indicative of the $^4He/^3He$ spectrum of the mantle, the positions of the recurring peaks may have some underlying significance. In light of the experimental partitioning data, these peaks could represent times at which unusually large amounts of depleted mantle were produced, suggesting large temporal variations in global mantle melting rates.

One way to calculate ages for the $^4He/^3He$ peaks would be to assume a certain He evolution model and use it to obtain age estimates. However, there are a wide range of He evolution models that can be envisaged[10,18], and so a large range of non-unique depletion ages could be produced. Another approach is to look in the geologic record for independent estimates of the timing of mantle melting events, and in particular to see if the pattern of ages can be correlated with the pattern of OIB $^4He/^3He$ peaks. The continental crust may provide such a record of melting events. Studies of zircon U–Pb and Lu–Hf ages have suggested that there were a number of pulses of continental crust growth[4,5,19]. The main zircon age peaks are at 1.2, 1.9, 2.7 and 3.3 Gyr (Fig. 2). As the continental crust was extracted from the mantle by partial melting[3], these peaks could record pulses of mantle melting. Alternatively, they could merely represent areas of continental crust that have randomly escaped tectonic recycling and may not imply increased continental crust growth rates[2,20]. In this case, there should be no correlation between mantle depletion events and zircon age peaks.

The pattern of the zircon age peaks is distinctive, with a number of peaks in the Archaean and a large gap after 1.2 Gyr (Fig. 2). This is reminiscent of the pattern of the He peaks, where there are a number of peaks at low $^4He/^3He$ and then a large gap above $70 \times 10^3$. If one correlates the patterns on this basis, the points produce a line with a very high $R^2$ (0.9986, see Supplementary Table 1 for data points) on a He evolution diagram (from here on referred to as the He-continental crust (He-CC) correlation). Although other choices of how to correlate the peaks will produce linear correlations (because both the He and zircon age data sets are monotonically increasing), they have lower correlation coefficients.

More significantly, the slope of the line is not random. If one projects the He-CC correlation to the present day, it yields a value of $^4He/^3He$ of $(92.2 \pm 0.7) \times 10^3$ (±s.e.), which matches the value of the dominant peak in modern MORB of $(91 \pm 1.5) \times 10^3$ (error is width of peak, Fig. 1). Likewise, projected back to 4.55 Gyr ago, the age of the Earth, it yields a value of $(5.6 \pm 0.8) \times 10^3$ (±s.e.), matching the value estimated for the initial Earth from the atmosphere of Jupiter, $(6 \pm 0.2) \times 10^3$ (ref. 6). The independent prediction of these two fundamental values by the He-CC correlation is strong evidence that the He and zircon peaks are causally related. The slope is a robust feature of the data and is not controlled by any one point. For instance, if only the four main peaks (1.2, 1.9, 2.7 and 3.3 Gyr) are used, the $R^2$ is 0.9994, the $t = 0$ intercept is $(91.1 \pm 0.8) \times 10^3$ and the $t = 4.55$ Gyr intercept is $(7.3 \pm 0.7) \times 10^3$. If the He-CC correlation was spurious, or the He peaks themselves were simply the result of over-sampling certain locations, it would require three highly improbable coincidences: (1) the correlation of $^4He/^3He$ peaks from island

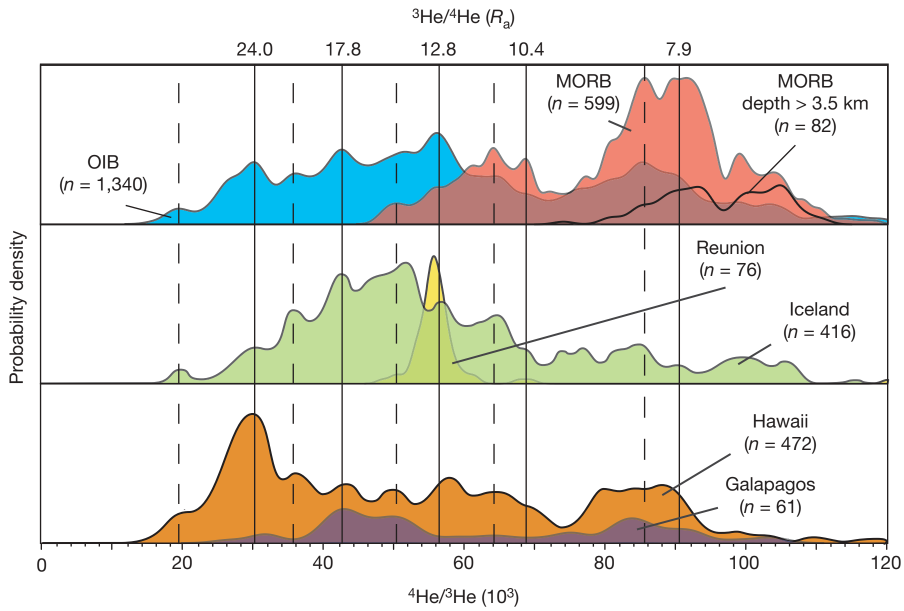


**Figure 1 | Globally recurring $^4He/^3He$ peaks in oceanic basalts.** Curves show probability density functions (PDFs, $n$ = number of data points in the distribution) of $^4He/^3He$ ratios in ocean island basalts (OIB: blue), mid-ocean-ridge basalts (MORB: red, unfiltered; dredged from depths >3.5 km, black line), Iceland (green), Reunion (yellow), Hawaii (orange) and Galapagos (purple). Data are taken from ref. 31. Vertical lines show peaks that are present in more than one ocean island (see Supplementary Fig. 1 for histograms of the data as well as distributions for other islands) and so are unlikely to be sampling bias artefacts. Solid vertical lines are for peaks that correspond to the four major zircon age peaks[4,5] (see Fig. 2). Dashed lines correspond to smaller zircon age peaks, except for the peak at $20 \times 10^3$, which has no matching zircon peak. The $^3He/^4He$ values for the peaks are given along the top, in units of $R_a$ ($R_a$ is the $^3He/^4He$ ratio of the atmosphere). The MORB database has not been filtered, so samples with $^4He/^3He$ lower than $75 \times 10^3$ are probably attributable to the influence of nearby plumes, because the peaks are not present when the data are filtered for depth (see Supplementary Fig. 1). Thus those data could be transferred to the OIB PDF, but the peak positions would not be affected. The zircon age peaks in the range $(20–70) \times 10^3$ are well expressed in the OIB $^4He/^3He$ data, but less so after that. The $69 \times 10^3$ peak is barely visible as a shoulder on the Hawaii and Iceland data, and is perhaps represented by two points in the Reunion data that make a small peak. It is much clearer in the MORB data. The peak at $86 \times 10^3$ in the OIB data is largely due to Atlantic islands (Azores and Cape Verdes), though it is present, if less sharp, in Pacific islands (Galapagos) as well.

to island, (2) the correspondence of those peaks with the zircon age peak pattern and (3) the prediction of both the present-day MORB and initial Earth $^4$He/$^3$He values.

If the He-CC correlation is significant, it implies that the crustal growth has been punctuated by periods of unusually high growth rates[4,5,19], and that these pulses are recorded in both the mantle (as He peaks in OIB and MORB) and the crust (as zircon age peaks). These events would be catastrophic (as opposed to uniformitarian), and it is not clear that there are any Phanerozoic analogues. Interestingly, komatiites have a similar age distribution as the melting pulses, with most being erupted at 3.3, 2.7 and 1.9 Gyr ago. Perhaps their unique geochemistry provides clues to the nature of the large melting events.

A clear requirement of the He-CC correlation is that depleted mantle domains have been preserved for billions of years against mantle convection. How this happens is not clear, and neither is the spatial distribution of the domains within the mantle. A number of papers have pointed out that many ocean islands are spatially associated with seismic low-velocity areas at the core–mantle boundary, and that these regions may be the ultimate source of OIB[21–23]. Such a dense boundary layer would be a good place to preserve depleted heterogeneities against convective rehomogenization for long time periods.

The linear form of the He-CC correlation is a strong observational constraint on any He evolution model. A wide range of He models have been proposed, many of which produce linear $^4$He/$^3$He evolution owing to the degassing of the mantle[10,18]. How much of the mantle has been degassed is not constrained by the He peaks, but as the entire spectrum of $^4$He/$^3$He values (below $91 \times 10^3$) is interpreted

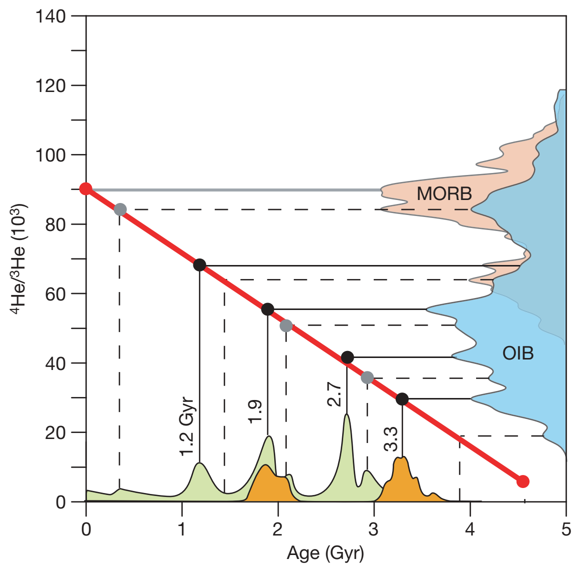


**Figure 2 | Correspondence of OIB and MORB $^4$He/$^3$He peaks with continental crust zircon age peaks.** Probability distribution functions of OIB (blue) and MORB (red) from Fig. 1 are shown along the right side of the figure. Crustal zircon age distributions are shown along the horizontal axis (orange[5], green[4] fields). There are seven He peaks in the OIB and MORB distributions that can be correlated to the zircon age peaks (connected by solid and dashed lines). A regression through these points (black, major peaks; grey, minor peaks) yields an $R^2$ of 0.9986, an intercept at $t = 0$ of $(92.2 \pm 0.7) \times 10^3$ and an intercept at 4.56 Gyr of $(5.6 \pm 0.8) \times 10^3$ (thick red line). Thus it independently predicts the dominant peak in the MORB data ($(91.0 \pm 1.5) \times 10^3$, filled red circle at age = 0 Gyr) and the initial $^4$He/$^3$He of the Earth ($(6.0 \pm 0.2) \times 10^3$, estimated from the atmosphere of Jupiter[6], red filled circle at age = 4.55 Gyr). The thick red line represents the He isotopic evolution of the MORB source. The $^4$He/$^3$He evolution is linear with time because He is not recycled back into the mantle by subduction, and so the mantle is an open system with respect to He (see text). Two He peaks do not have matching zircon peaks, corresponding to ages of 3.9 and 1.4 Gyr. Thus one prediction of the He-CC correlation is that zircon age peaks might be found at these ages.

to reflect ancient, depleted mantle domains, there is no requirement (or evidence) for an undepleted mantle reservoir or for layered convection in this interpretation of He isotope systematics.

If there is no primitive mantle, it implies that the entire mantle has been processed by melting and consists mostly of depleted, harzburgitic material with a subordinate amount of recycled oceanic crust. Such a view has been previously proposed and is consistent with seismic scattering observations[24–27]. If this is the case, then most of the incompatible trace elements in the mantle are in the volumetrically minor eclogitic components, whereas most of the compatible elements are in the harzburgitic matrix. Helium is unusual in that it is an incompatible element that is not enriched in the recycled component because it degasses from erupted lavas and, from there, escapes to space. Thus both depleted and recycled components may have roughly similar He concentrations. Indeed, He concentrations may be higher in the ancient depleted domains as they seem to have acted as closed systems for much of Earth's history, whereas the recycled components may have undergone multiple cycles of degassing. In either case, harzburgitic material makes up >70% of the mantle in this view and so would contain the bulk of the Earth's He. This may explain the apparently paradoxical situation that OIB are enriched in nearly all incompatible trace elements and isotopic systems[28] (reflecting the contribution from the recycled components), but have depleted He isotopes (reflecting the presence of ancient depleted harzburgite material that makes a negligible contribution to the trace element budget of the magmas but dominates the He budget).

The ultimate cause of these large melting events is not clear. Presumably, they are related to large releases of heat from the mantle (though a large flux of volatiles could also produce melting). Numerical mantle convection models have produced large variations in mantle heat flux owing to variable rates of mantle convection[29,30]. Perhaps the large melting events record such large-scale mantle overturns.

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**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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