Helium isotopic memories of episodic mantle melting and crustal growth

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In a recent article in *Nature*, Parman[1] has made the intriguing suggestion that helium isotope ratios in oceanic extrusions are relics of episodic large-scale melting of the earth's mantle and attendant growth of continental crust.

When a region in the silicate mantle of the earth undergoes partial melting, the melt or magma rises to the surface where it extrudes as basaltic rock, and delivers a chemical and isotopic message to the geochemist. As recently formed, pristine material sampling relatively large volumes of the mantle, two main types of oceanic basalts have been studied for inferences on the chemical composition and evolution of the mantle[2]. One is the Mid Ocean Ridge Basalt (MORB) which erupts all along the 60,000 km-long mid ocean ridge system by melting of the mantle rising under the ridge due to convection. The MORB spreads as new ocean crust on either side of the ridge, and is eventually subducted back into the mantle at a convergent plate margin where it promotes partial melting of the overriding plate margin to give rise to island arc magmas. Because of some key chemical similarities of island arc magmas to the continental crust, the latter is believed to grow in time by accreting the former, besides by also other less understood processes. The second type of oceanic basalt is produced by the melting of a narrow column of hot material known as mantle plume rising from the base of either the upper mantle at a depth of 660 km or the lower mantle at a depth of 2900 km. This melt extrudes on the ocean floor away from plate margins as Ocean Island Basalt (OIB), a well-known example being the Hawaiian Islands in the mid Pacific. MORB and OIB can occur together when a mantle plume intersects a segment of the mid ocean ridge system, such as on Iceland.

As tracers or probes of mantle-melting processes, geochemists have analysed relative abundances of the so-called incompatible trace elements, and isotopic composition of daughter elements (Sr, Nd and Pb) of long-lived radioactive elements (Rb, Sm and U) in MORB and OIB[2]. Because of their large ionic radius and high ionic charge, incompatible elements preferentially enter the melt phase which transports them to the surface. While melting thus fractionates parent–daughter ratios between melt and its solid residue, it leaves the isotopic ratios intact, a feature useful in timing depletion events due to melt removal. Such analyses indicate cumulative depletion of the mantle in incompatible elements and their complementary enrichment in the crust. However, the degree of depletion is much higher in the upper mantle sampled by MORB, than in the lower mantle sampled by OIB. This suggests that the upper and lower mantles are chemically and physically isolated, with each convecting independently. The lower mantle could indeed be close to its original composition, with the chemical and isotopic variability in OIB arising from the entrainment of depleted upper-mantle material in the rising plume.

Being chemically inert and volatile, noble gases would partition strongly into the melt phase, and then escape to the atmosphere on reaching the surface. Thus, unlike the refractory incompatible elements, noble gases will not be recycled from surface materials to blur the record of melting processes. Of the various noble gases[3,4], helium has been particularly instructive. Among the two isotopes of helium, ^{3}He could have been only inherited by the earth at its formation from the solar nebula, whereas ^{4}He is also produced continuously within the earth by alpha decay of uranium and thorium. Hence the present-day ^{4}He/^{3}He ratios measured in MORB and OIB will reflect the relative proportions of inherited (primordial) and radiogenic helium in the mantle regions sampled by them. ^{4}He/^{3}He ratios in MORB are relatively uniform and high at ~90×10^3, while those in OIB range from 20 to 80×10^3. This difference has so far been taken as support for the two-layer model inferred from incompatible trace elements. The upper mantle is almost homogeneously depleted of essentially all its primordial ^{3}He (and also ^{4}He), but the deeper mantle retains most of its primordial He, with the variability of helium ratios in OIB being due to its mixing with highly radiogenic He from the upper mantle in the rising plume.

Parman[1] has not reported any new He data, but has examined the available data in the light of the recent geophysical evidence against a two-layer convection, and his counter-intuitive finding[5] that on partial melting, the solid residue would lose its U and Th more effectively than He. The latter implies that the isotopic composition of helium remaining in the solid residue would grow much slower than the rest of the mantle. Parman in fact envisages that the removal of U and Th could even be so complete during intense and large melting events, as to freeze or arrest helium ratio in the depleted domains at the distinctive value of the bulk mantle at that time.

Parman's departure from the conventional picture is that such highly depleted mantle pockets with frozen or nearly frozen helium ratios are still preserved in the mantle and sampled by OIB. The spectrum of helium ratios in OIB shows distinct peaks (Figure 1). While the shape of this spectrum (relative heights of peaks and valleys) could be an artifact of uneven sampling of OIB, Parman stresses that that the peak positions match in the spectra of widely separated islands, and hence must have an underlying significance. In his own words, 'the peak positions represent times at which unusually

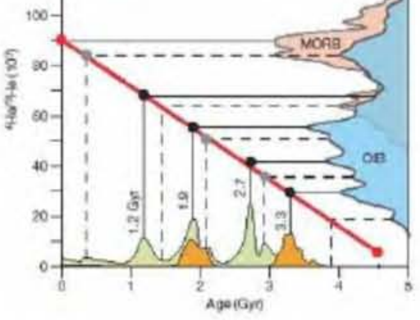

Figure 1. Helium isotopic spectrum in OIB and MORB and correlation of helium peaks with crustal zircon age peaks, reproduced from Parman[1]. The thick red correlation line represents He isotopic evolution of the bulk mantle. Reprinted from *Nature* with permission.

large amounts of depleted mantle were produced, suggesting large temporal variations in global melting rates'. As continental crust is extracted through mantle melting, major pulses of mantle melting should be reflected in corresponding major pulses of crustal growth. U–Pb ages of zircon minerals[6] marking times of pristine additions to the crust, do show conspicuous peaks at 1.2, 1.9, 2.7 and 3.3 billion years (Ga), as shown on the x-axis of Figure 1, which correlates well (thick red line) with the major peaks (left vertical axis) in the OIB spectrum (shaded blue along the right vertical axis). The linear correlation line, projected to the present time, yields a helium ratio matching well with the dominant peak in MORB (shaded red) and a ratio matching the estimated initial ratio in the earth when projected back to 4.55 Ga (age of the earth). Parman cites this predictive power of the correlation line to not rule it out as fortuitous. The linear form of the correlation line is in accord with theoretical models of ^{4}He/^{3}He evolution within the earth, allowing for degassing of helium from extruded melt.

Although impressive in explaining the different He isotopic ratios sampled from the mantle, Parman's model requires scenarios that are difficult to conceive. Unlike most other mantle evolution models mentioned in the beginning, his model does not require a still surviving primitive mantle reservoir (regardless of its size) and hence a layered convection to preserve it, and is in fact consistent with whole mantle convection favoured by recent geophysical evidence. As whole mantle convection will rehomogenize large depleted mantle domains envisaged in this model, it is necessary to somehow isolate a small representative fraction or derivative from each domain well before its homogenization and store them in a place for sampling by OIB through much of the earth's history. As the thin and inhomogeneous D″ layer at the core–mantle boundary is believed to be the ultimate source of OIB, Parman suggests that the isotopic slices of mantle melting could be stacked up in this layer. Even more difficult to visualize is how each plume scoops out a portion of all or some of these slices before its upward journey and resists mixing with modern mantle material over a 2900 km traverse to the surface. It is also not clear why large-scale melting took place nearly periodically at 3.3, 2.7, 1.9 and 1.2 Ga, but suddenly ceased after 1.2 Ga. There are also difficult issues of reconciling this model with isotopic heterogeneities identified[7,8] from other radiogenic isotope systems like K–Ar, Rb–Sr, Sm–Nd and U–Pb. However, this model is bound to attract considerable attention, and force geochemists and geophysicists to reconsider their pet theories on isotopic images of the mantle.

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