Probing the Hadean world with noble gases

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Earth's violent accretion likely generated multiple magma oceans. In particular, the Moon-forming giant impact is often thought to have produced a whole mantle magma ocean, which would have homogenized any pre-existing chemical heterogeneity within the mantle. The ratio of primordial ^{3}He to primordial ^{22}Ne in the mantle preserves a record of magma oceans on the early Earth. Importantly, the ^{3}He/^{22}Ne ratio of the Earth's shallow depleted mantle is significantly higher than the deep mantle. To explain this observation, I propose that at least two giant impact-induced atmospheric blow-off and magma ocean degassing episodes are required and that the last giant impact did not generate a whole mantle magma ocean. Accordingly, if plumes are derived from Large Low Shear Wave Velocity Provinces (LLSVPs) at the base of the mantle, then LLSVPs (i) are not remnants of crystallization of a global magma ocean associated with the last giant impact; and (ii) are not dense cumulate piles that crystallized from the last magma ocean at shallow depths and were subsequently gravitationally overturned to the core-mantle boundary, as shallow cumulates would be the most degassed (with the highest ^{3}He/^{22}Ne ratios). LLSVPs either correspond to crystallization products from an earlier magma ocean or are produced through a mechanism not associated with magma oceans.

Mantle Xe isotopic constraints indicate that the final mantle outgassing and atmospheric blow-off events inferred from ^{3}He/^{22}Ne ratios were accomplished between ~30 to 65 Myrs after the start of the Solar System. Therefore, catastrophic outgassing associated with giant impacts, including the Moon-forming impact, must have occurred within this time window. Previous calculations of impact-induced atmospheric erosion have, however, found that it is difficult to completely remove the atmosphere from a body as large as Earth by a giant impact. The need for atmospheric loss inferred from the noble gas data can be reconciled with the dynamics of giant impacts by considering the new high-spin Moon formation hypothesis. I will discuss the origin of Earth's early atmosphere in light of the new high-spin model for Moon formation and new noble gas data from mantle-derived rocks. I propose that major differences in the noble gas signatures of terrestrial planetary atmospheres reflect the diverse outcomes of late impact events on each planet.

Of ancient reservoirs and recycled noble gases

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The noble gases provide important constraints on planetary volatile cycling and our understanding of mantle structure and dynamics. For example, OIBs have ^{129}Xe/^{130}Xe ratios closer to the atmospheric ratio than MORBs, which could either reflect a higher proportion of recycled Xe in the OIB source or the sampling of an ancient, less-degassed reservoir (>4.45 Ga, since ^{129}I, which produces ^{129}Xe, is extinct after ~100 Ma). However, measurements of mantle-derived noble gases indicate that OIB sources do not have a higher proportion of recycled atmospheric Xe relative to MORB sources. The observation that the differences in the Xe isotopic composition of MORBs and OIBs cannot be attributed solely to recycling requires that OIBs sample a reservoir that evolved with a lower I/Xe ratio than the MORB source. Thus, differences in the degree of outgassing between the MORB and OIB sources must have been established by 4.45 Ga and subsequent mixing between the two reservoirs must have been limited. As a result, if OIBs are derived from the large low shear wave velocity provinces (LLSVPs) at the base of the mantle, then the Xe data require these features to be at least as old as 4.45 Ga.

Although the differences in MORB and OIB Xe isotopic composition cannot be solely due to recycling, new high-precision Xe measurements in MORBs and OIBs indicate that ~80-90% of the Xe in the MORB and OIB sources could be attributed to recycled atmospheric Xe. Thus, recycling of atmospheric noble gases is a process important to mantle volatile budgets. Our ability to constrain mantle source ^{129}Xe/^{130}Xe and ^{40}Ar/^{36}Ar ratios through multiple step crushing experiments now reveals significant heterogeneities in these ratios among mantle sources. For example, along 500 km of the Southwest Indian Ridge, in a region removed from any known plume influence, we observe ~50% and ~80% of the total mantle variation in ^{40}Ar/^{36}Ar and ^{129}Xe/^{130}Xe, respectively. Such large variations indicate a MORB source that has experienced heterogeneous recycling and mixing of material metasomatized by subduction zone fluids carrying recycled atmospheric Ar and Xe. Thus, a more complex picture emerges from new high-precision noble gas data, of a planetary interior that has both retained broad ancient degassing features and developed fine-scale heterogeneity from a chaotic, integrated history of volatile cycling.

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